Optical Communication Lasers

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Criteria for Light Sources

- A carrier is characterised by its amplitude, frequency and phase

$$c(t) = A\cos(\omega_c t + \phi) \qquad \ldots\ldots\ldots 3.1$$

- Where its amplitude, A, circular frequency w_c, and phase ϕ are time-invariant

Criteria for Light Sources

- In practice, a light source driven by a constant current source has the following form:

$$c(t) = \sum_i A_i \cos[\omega_{c,i} t + \phi_i(t)] \quad \text{........3.2}$$

- Where each carrier at frequency $w_{c,i}$ represents a **longitudinal mode** and $\phi_i(t)$ is a random phase noise. The carrier with the largest amplitude A_i is called the **main mode** and the others are called the **side modes**

Multimode Sources

- A multimode source is not good for communications
- Consider a light source generating three longitudinal modes:

$$c(t) = A_{-1}\cos[(\omega_c - \Delta\omega)t] + A_0\cos(\omega_c t) + A_1\cos[(\omega_c + \Delta\omega)t]$$

- Where the random phase noise $\phi_i(t)$ for each carrier is ignored here

Multimode Sources

- If the carrier is amplitude modulated by a square pulse with duration T_0 . The transmitted signal has the form:

$$p(t) = rect(t, T_0)c(t) = rect(t/T_0)\{A_{-1}\cos[(\omega_c - \Delta\omega)t] + A_0\cos(\omega_c t) + A_1\cos[(\omega_c + \Delta\omega)t]\} \stackrel{\text{def}}{=} p_{-1}(t) + p_0(t) + p_1(t)$$

- Where $rect(t,T_0)$ is a unit rectangular pulse of duration T_0 .

Multimode Sources

- If the three modes propagate in a fibre at speeds $v_g - \Delta v_g$, v_g , $v_g + \Delta v_g$,

respectively, the received pulse over distance L is:

$$r(t) = p_{-1}(t - \tau_{-1}) + p_0(t - \tau_0) + p_1(t - \tau_1)$$

$$\tau_0 = \frac{L}{v_g} \qquad \tau_{\pm 1} = \frac{L}{v_g \pm \Delta v_g} \approx \tau_0 (1 \mp \frac{\Delta v_g}{v_g})$$

Multimode Sources

- If $\Delta\, v_g << v_g$,
- The detected photocurrent is proportional to the square of the received signal:

$$i_{out}(t) = \mathcal{R}|r(t)^2| \approx \mathcal{R}\{A_{-1}^2 rect[(t-\tau_{-1}), T_0] + A_0^2 rect[(t-\tau_0), T_0] + A_1^2 rect[(t-\tau_1), T_0]\}$$

- Where $\mathcal{R}$ is the responsivity in photodetection and the high frequency cross terms have been dropped

Multimode Sources

- The final detected pulse has a broader width of $T_0 + 2(\Delta v_g / v_g)\tau_0$
- The pulse broadening is illustrated in figure (3.1) and results from a phenomenon called **fibre dispersion**

Multimode Sources

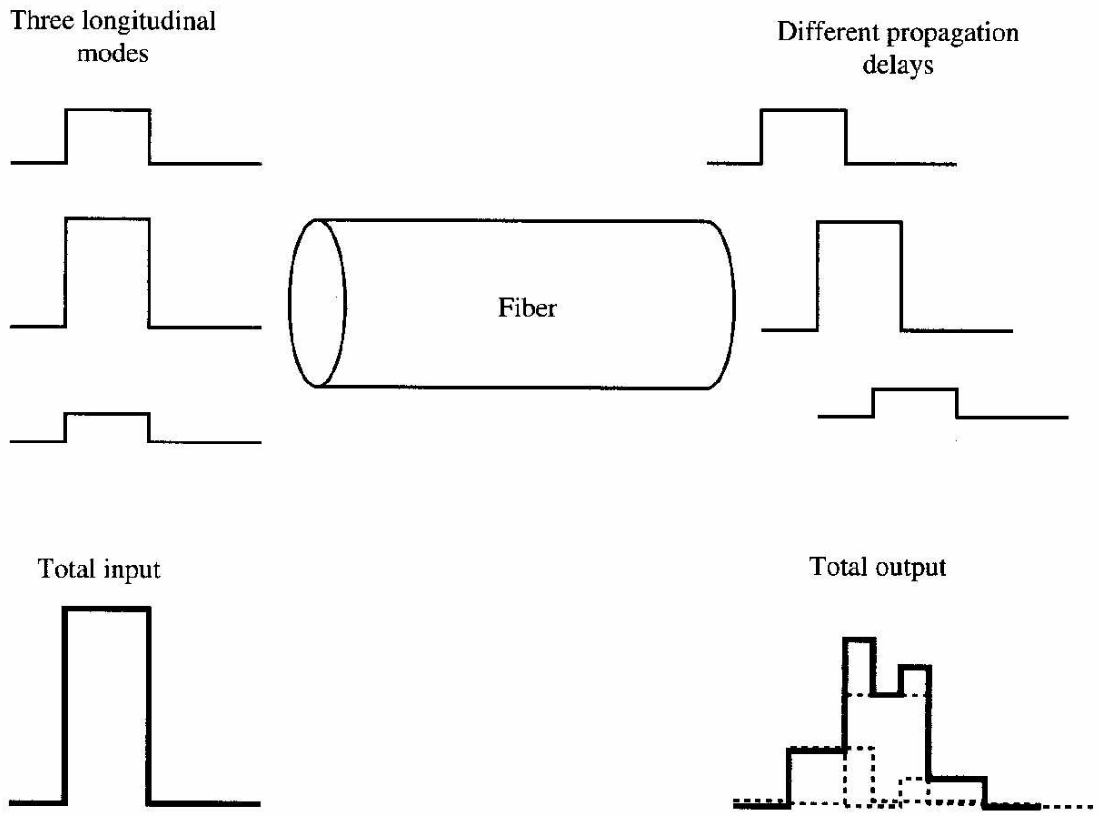


Figure 3.1 Illustration of pulse broadening because of multiple carriers and fiber dispersion.

Criteria for Light Sources

- A light source as expressed by equation (3.2) has other problems
- The amplitudes A_i in equation (3.2) can fluctuate and result in random power distribution among the longitudinal modes.
- This random intensity fluctuation causes two kinds of laser noise:
  - Relative intensity noise (RIN)
  - Mode partition noise (MPN)

Phase Noise Problem

- Consider a light source generating a single longitudinal mode carrier

$$c(t) = A_0 \cos[\omega_c t + \phi_n(t)]$$

- Where $\phi_n(t)$ is the phase noise. Assume the carrier is phase modulated and coherently detected at the receiver, the transmitted signal has the following form:

$$s_{PM}(t) = A_0 \cos[\omega_c t + k_{PM} m(t) + \phi_n(t)].$$

Phase Noise Problem

- An ideal phase demodulator that extracts the phase term of the signal wrt $w_c t$ would give the following demodulated output:

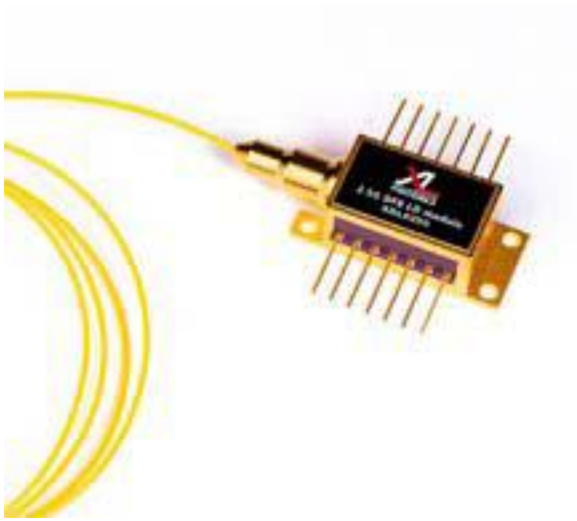
$$\hat{m}(t) = k_{PM} m(t) + \phi_n(t).$$

- Therefore, the output is distorted by the phase noise $\phi_n(t)$. To reduce this effect, we need to use a large k_{PM} .
- The trade-off is a larger transmission bandwidth

Light Source Design Criteria

- **Single longitudinal mode** lasers have been developed such as:
  - Distributed feedback lasers (DFL)
  - Distributed Bragg reflection lasers (DBR)
  - They are both based on Bragg reflection to generate only a single mode
- **Low Noise.** Laser noise includes: phase noise, relative intensity noise (RIN) and mode partition noise. Low noise is important to achieve a low bit error rate (BER) in digital communication and a large SNR in analogue communications

XL Photonics, 2.5 Gbps DFB Laser Diode Module *XDL0250B-001*



- 1550 nm distributed feedback laser
- Low threshold current
- High optical power available
- 2.5 Gbps (NRZ) direct modulation
- Stable single longitudinal mode operation
- Internal thermoelectric cooler and monitor photodiode
- Built-in optical isolator
- Single mode fiber pigtail with connector ; 25 Ω impedance-matched RF input

The Syntune S3500 is a tunable DBR laser module

C-band tunable 10 Gb/s transmitter
Full C-band tuning
(89 channels at 50 GHz spacing)
High, flexibly adjustable output power, from 9 to > 13 dBm
Low power consumption, typically < 2.5 W at 75°C
High side-mode suppression ratio > 40 dB
Independent power and wavelength control
stabilisation to within ±2.5 GHz over life, compatible with 50 GHz ITU grid spacing
Polarisation maintaining fiber pigtail

Applications
DWDM transmission systems
Tunable DWDM transponders and transceivers

Optical packet or burst-mode switching

Light Source Design Criteria

- **Small line width.** If there is no phase noise, the power spectral density (PSD) of the carrier in equation (3.1) is the sum of two delta functions at $\pm w_c$ Because of the phase noise in equation (3.1), the PSD is not a sum of delta functions but has a finite nonzero width around each $\pm w_c$.
- **High output power**. A high output power can either provide a large received SNR or allow a longer distance transmission. Light sources must be designed with a high external coupling efficiency and high optical confinement.

Light Source Design Criteria

- **Low threshold current.** For laser diodes, lasing cannot start until the bias current is higher than a minimum value called the threshold current, I_{th}. The output power is proportional to *$(I_{bias} - I_{th})$*. A lower threshold current allows a smaller bias current for the same output power. This alleviates the power dissipation problem.
- **Wavelength** affects propagation characteristics. First generation laser diodes operated at a wavelength of around 870 nm using GaAs laser diodes. To deliver low fibre attenuation and dispersion III-V compounds have been successfully developed. The wavelengths are now 1300 nm and 1550 nm.

Light Source Design Criteria

- **Large modulation bandwidths**. There are two major modulation techniques: **direct modulation** and **external modulation**. Direct modulation is the most commonly used. This uses the transmitted signal to drive the light source directly. The light source must be able to respond fast enough to the time-varying input signal. In external modulation, an external device modulates the CW output from the light source.
- **Small linewidth broadening.** When a light source is directly modulated, its output linewidth is broadened. This is due to the refractive index modulation of the light source that results in pulse dispersion. Quantum-well lasers have been reported for small linewidth broadening.

Light Source Design Criteria

- **Linearity.** For analogue communications, signal distortion due to light source non-linearity should be minimised. Non-linearity will introduce higher harmonic terms and cross-talk.
- **Tunability.** For applications such as WDM the laser diode should be tuneable to different wavelengths. A tuneable laser diode has two or more external contacts that allow users to tune the output wavelength. A tuneable laser diode should have a tunable range of several thousand GHz.

Light Source Design Criteria

- What is required is:
  – High output power; Low threshold current; Small linewidth; Large modulation bandwidth; Low noise; Good tuneability
- To provide better stability of output power and wavelength an advanced laser diode is packaged with: a photo-detection circuit to monitor the output power, an isolator to reject reflection from output coupling and an electronic cooler circuit to stabilise the operating temperature

Characteristics of CW InGaAsP Laser Diodes

Table 3.1 Characteristics of some state-of-the-art continuous wave InGaAsP laser diodes.

Manufacturer	Model No.	Wavelength (nm)	Linewidth (nm)	Output Power (mW) at mA	I_{th} (mA)	Remarks
BT&D	LSC2110	1300	3.00	1@45	20	
	XMT1300-1.2	1300	3.00	1@45	20	1.2 GB/s bandwidth
AT&T	237	1310	3.00	0.02@25	12	Very low I_{th}
	215	1300	—	2.5	18	
Epitaxx	ELA13-23B-FJS	1300	5	0.2@20	10	Very low I_{th}
NEC	NDL5730P	1300	2.00	2@40	20	
	NDL5650	1300	0.1	8@50	20	DFB
	NDL5730	1300	2.00	8@50	20	Internal monitor
	NDL5800P	1310	0.10	8@50	20	DFB, 2.5 GB/s on subcarrier
Toshiba	TOLD332S	1310	0.10	0.7@50	20	low RIN
	300S	1300	0.1	4.0@50	20	DFB

Characteristics of CW InGaAsP Laser Diodes

Fujitsu Microelectronics	FLD 130F2RH	1310	50 MHz	5.0	—	DFB, 33 dB side mode suppression
Mistsubishi Electronics	FU-31LD	1300	3.0	2.5@40	20	Backfacet monitor
America	ML-7901	1300	5.0	6.0@40	20	
	FU-42SLD-D	1300	3.0	10@100	20	
	ML-7901A	1300	3.0	26@100	20	High power
Lasertron	QLM1300MW	1300	3.0	1.0	—	12 GHz on subcarrier
Stantel	LYC7M1	1300	3.0	5.0@55	25	
Ortel	1515A	1310	5.0	2.0@70	20	10 GHz analog
	1540A	1300	< 1	4@65	15	5 GHz DFB
BT&D	TSL1000-1550	1550	< 100 kHz	0.5@100	20	Tunable over 40 nm, TE cooler

Characteristics of CW InGaAsP Laser Diodes

Table 3.1 (concluded)

Manufacturer	Model No.	Wavelength (nm)	Linewidth (nm)	Output Power (mW) at mA	I_{th} (mA)	Remarks
NEC	NDL 5850C	1550	0.1	5.0@55	25	DFB, 2.5 GB/s
	NDL 5650	1550	0.1	5.0@50	25	DFB
Toshiba	TOLD350S	1550	0.1	4.0@50	20	DFB
	TOLD350	1550	4.0	4.0@55	25	FP laser
Fujitsu	FLD150F3CH-AL	1550	0.2	100		DFB
Mistsubishi	ML-9701	1550	3.0	6.0@40	20	
Stantel	LYC 11M1	1550	0.1	5.0@80	50	DFB
Micracor	ML-02A/02B	1480–1560	10^{-6}	<5	—	Tunable external cavity

NOTE: (1) The list is by no means an exact representation of all advanced laser diodes. (2) Data given may have been changed by the original manufacturers. Please refer to the original data sheets for exact values. (3) Those laser diodes of a linewidth of 0.1 nm can actually have much smaller linewidths. The linewidth of 0.1 nm comes from the optical spectrum analyzer resolution.

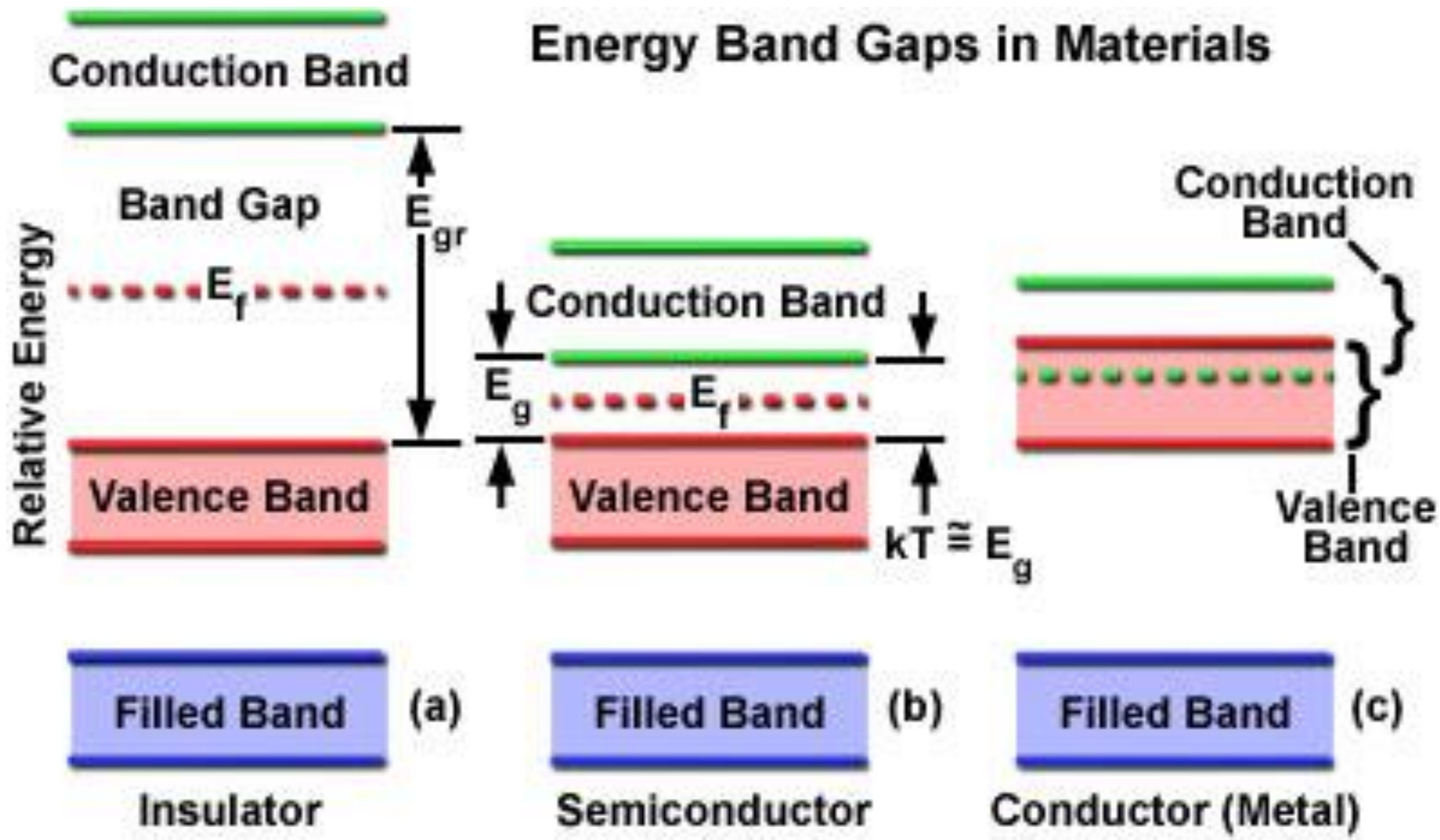
Characteristics of DFB Laser Diodes

Table 3.2 Detailed characteristics of DFB laser diodes in the TOLD33x series and TOLD38x series from Toshiba.

Item	Condition	Typical Value	Remarks
Threshold current	CW	20 mA	From linear extrapolation
Optical power	$I = 50$ mA	0.7 mW	
Wavelength	at 0.7 mW output	1310/1550 nm	TOLD332S/TOLD382S
Spectral linewidth	at 0.7 mW CW	20 MHz	
Side-mode suppression	at 0.7 mW output	35 dB	
Rise/fall time	$I_{bias} = I_{th}$	0.3 nsec	Modulation current is 30 mA
RIN	at 0.7 mW output	−145 dB	
Monitor current	at 0.7 mW output	0.1 mA	
Isolation ratio	at 0.7 mW output	30 dB	
Cooler capacity ΔT_c		maximum 35 °C	

NOTE: These laser diodes are usually packaged with an internal cooler circuit for temperature stability, a photodetector for output power stability, and an isolator for output wavelength stability.

Electronic Properties of Materials



P-N junction

- The core of a semiconductor light source is its p-n junction, often referred to as the active layer
- As shown in figure (3.2) the p-n junction is the interface between an N-type doped layer and a P-type doped layer
- A semiconductor light source has essentially the same p-n junction as a semiconductor diode
- There are two key differences between semiconductor light sources and ordinary p-n diodes

P-N Junction

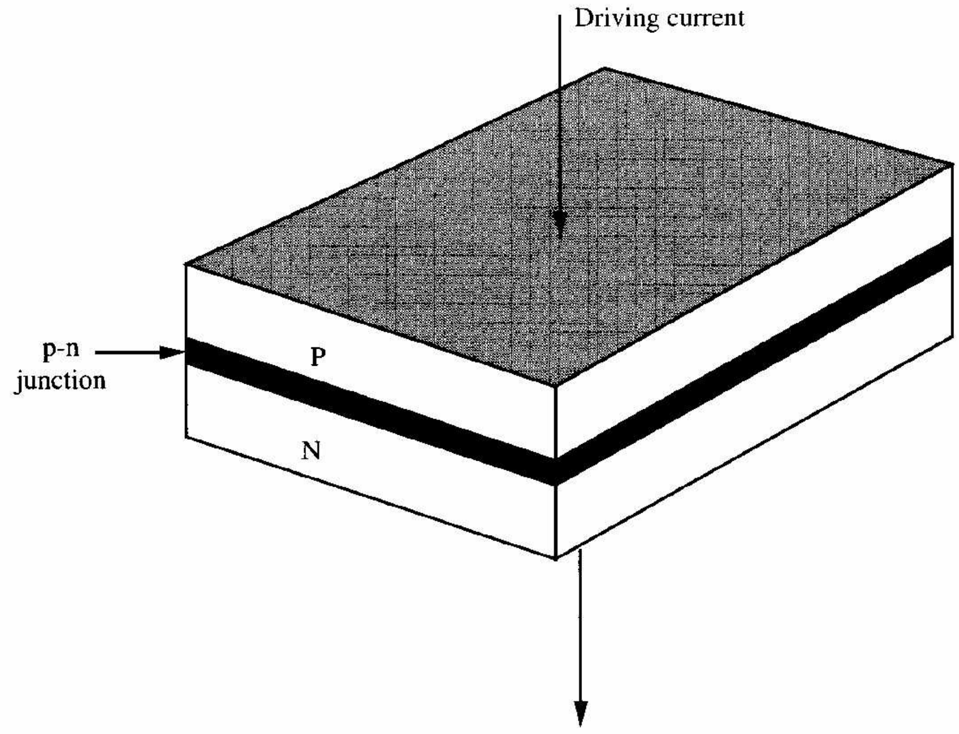
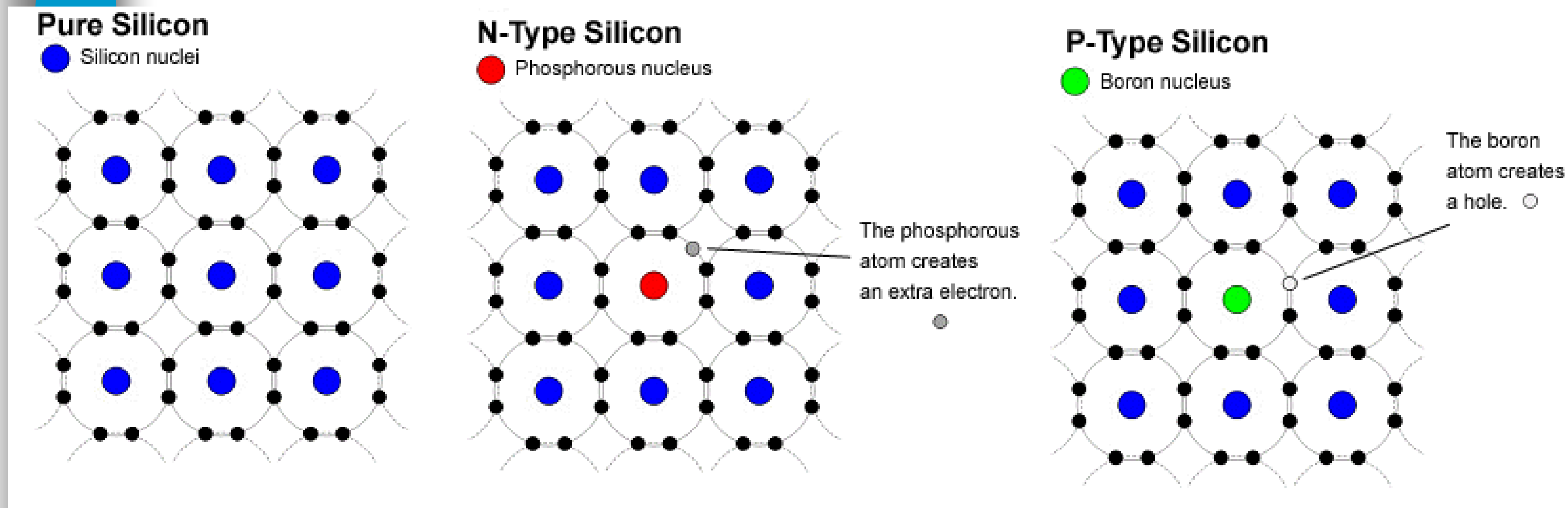


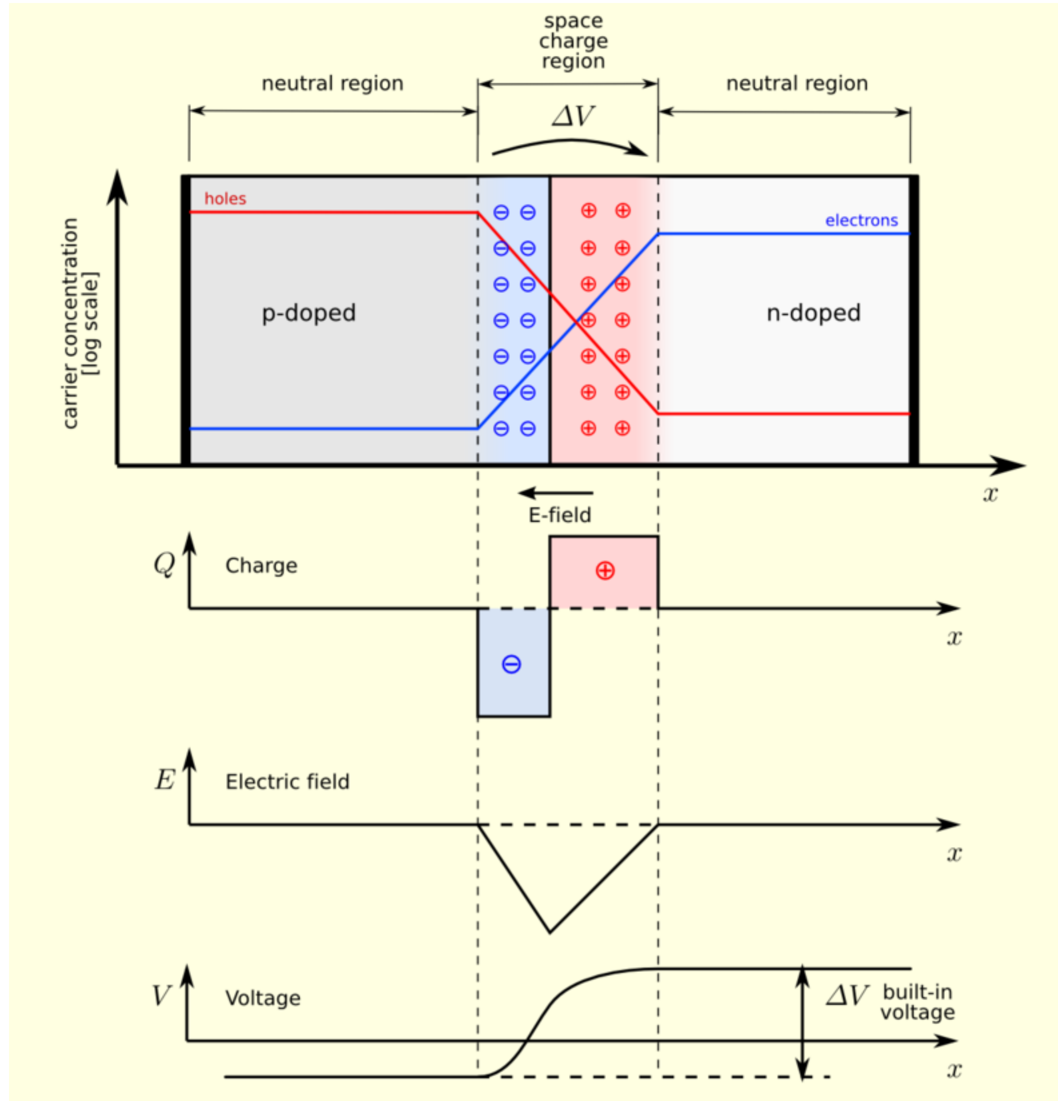
Figure 3.2 Illustration of a p-n junction.

[1] An N-type doped layer has free electrons from its N-type dopants, and a P-type doped layer has free holes from its P-type dopants. For background on p-n junction physics, read any standard textbook such as [9].

Doping of a silicon semiconductor lattice



- p-n junction in thermal equilibrium with zero bias voltage applied



P-N Junction

- The first difference is that the material used must have a direct energy bandgap as shown in figure 3.3
- Semiconductor has:
  - a conduction band above which electrons stay
  - A valence band below which holes stay
- In a direct bandgap material such as GaAs, electrons and holes have their minimum energies at the same momentum
- In an indirect bandgap material such as silicon, the energy bands have different momenta at their minimum energies, see fig 3.3

Direct and Indirect Bandgaps

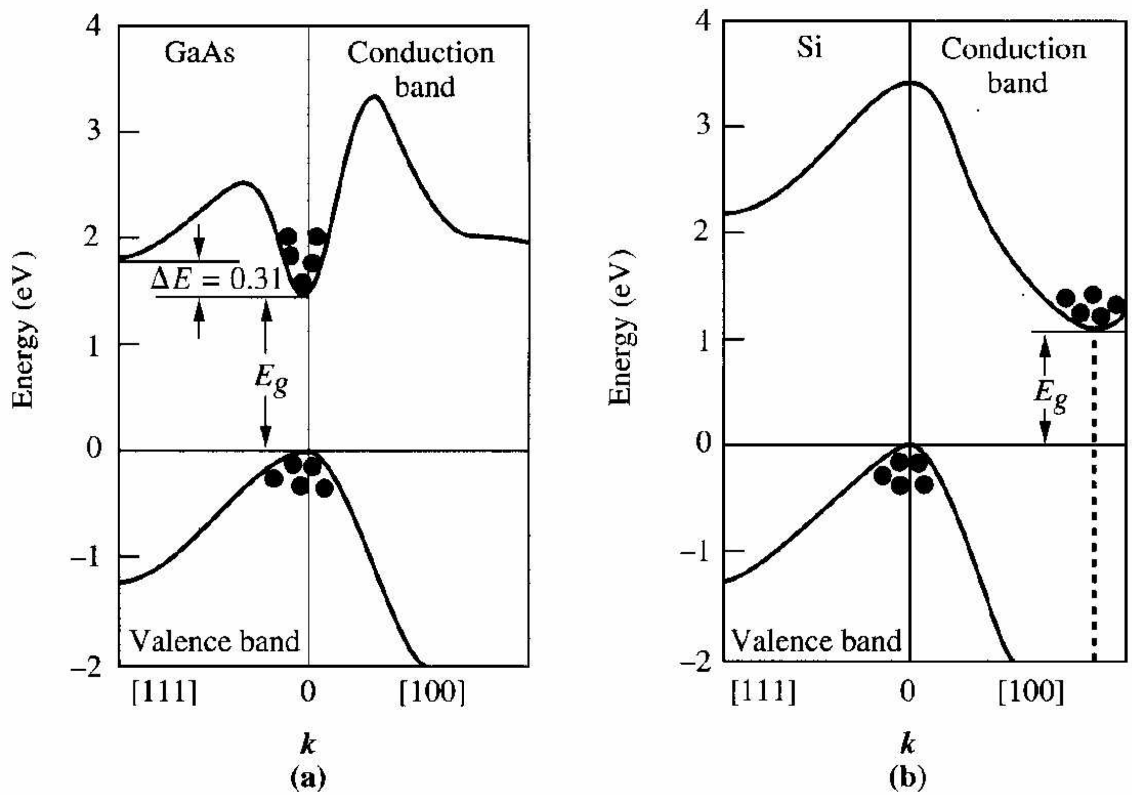


Figure 3.3 Illustration of direct and indirect bandgaps as a function of the momentum (k): (a) GaAs and (b) Si.

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P-N junction

- Due to conversion of momentum, an electron and a hole at the same momentum can directly recombine and generate a photon
- When they have different momenta, a third agent such as a semiconductor lattice has to be involved in a recombination process

Significance of direct bandgap

- A high direct electron and hole recombination rate (EHR) can be achieved because electrons and holes have the highest population at their minimum energy states.
- The energy release from each direct EHR is around the energy bandgap E_g photons generated by direct EHRs are around the same frequency.

$$f = \frac{E_g}{h}$$

Line broadening

- If EHRs are not direct but take place through an intermediate interaction with the material lattice, each recombination can generate two particles, not necessarily photons of smaller energies
- ΔE_1 and ΔE_2 with $E_g = \Delta E_1 + \Delta E_2$
- ΔE_1 and ΔE_2 are undefined and random, indirect EHRs result in an undesirably wide spectrum

Heterostructures

- Because of the large cavity loss, it is not possible to operate a laser diode at room temperatures using the simple p-n junction structure
- In 1969, room temperature semiconductor laser diodes became a reality with the use of heterostructures
- A heterostructure is a junction of two materials of different energy bandgaps crystally joined
- The junction is called a heterojunction

Heterostructures

- An n-P heterojunction is depicted in figure 3.4
- Because of the energy gap difference, we can see a jump of the valence band at the junction
- To confine both carriers and photons within the active layer, as illustrated in figure 3.5, a double heterostructure (DH) is used
- In the N-n-P double heterostructure (DH) illustrated the centre n type material has a smaller energy gap
- Capitals N or P indicates a larger bandgap energy than n or p

Heterostructures

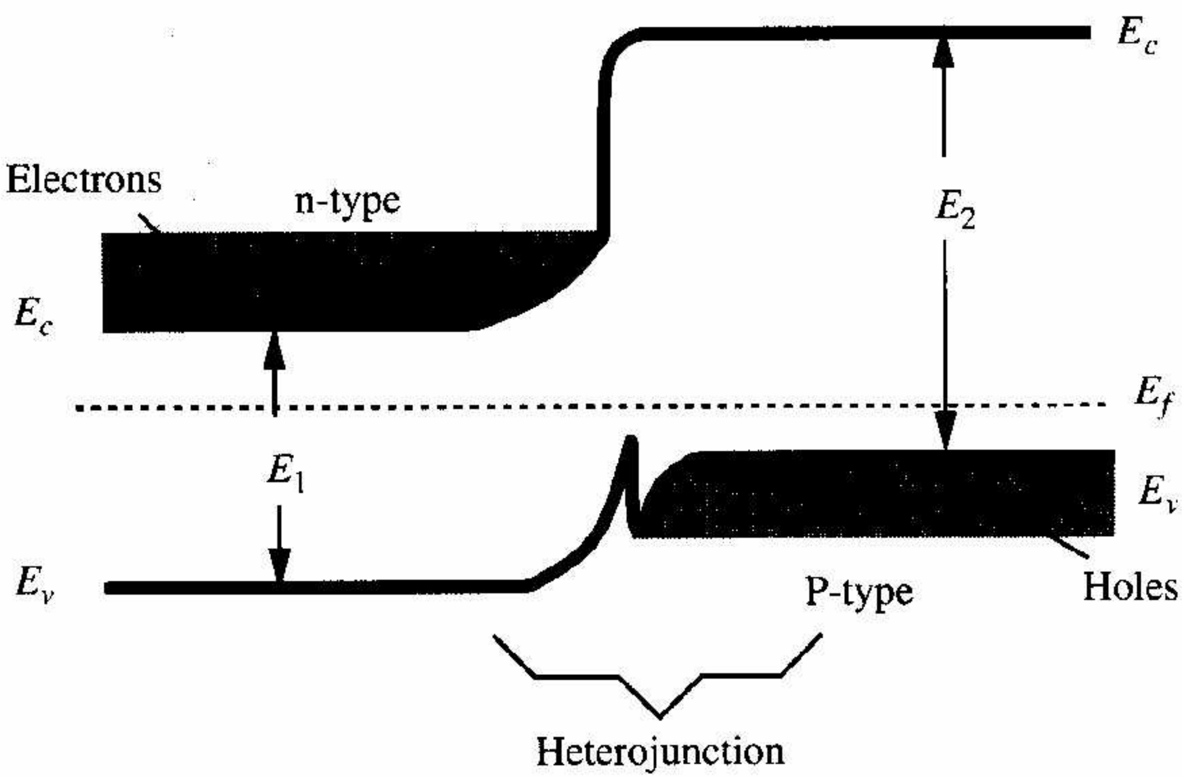
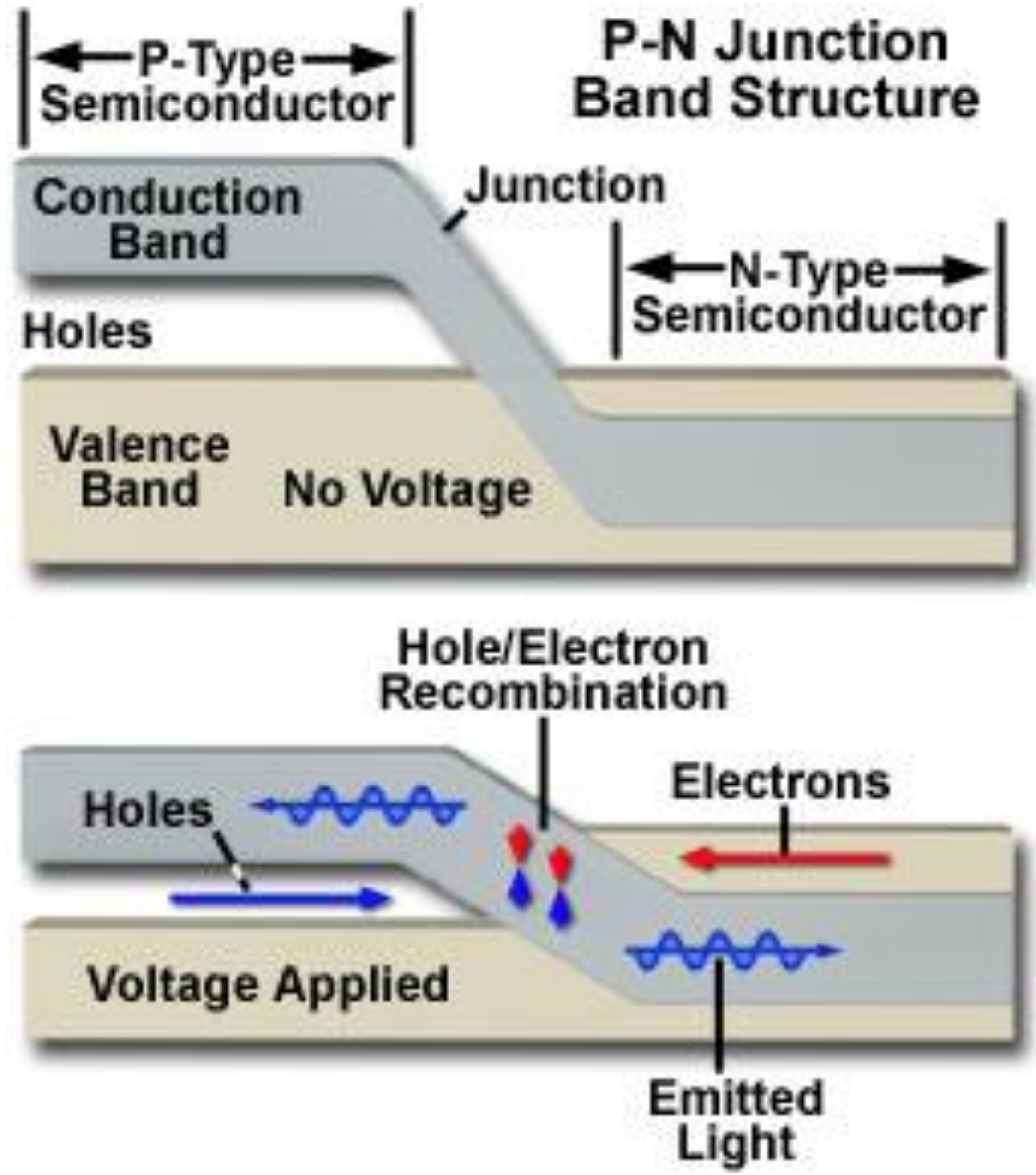
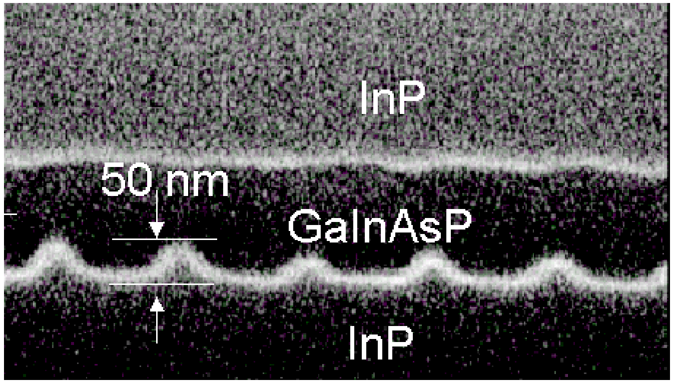


Figure 3.4 Illustration of an n-P heterostructure.


P-Type Semiconductor
P-N Junction Band Structure
Conduction Band
Junction
N-Type Semiconductor
Holes
Valence Band
No Voltage
Hole/Electron Recombination
Electrons
Holes
Voltage Applied
Emitted Light

Heterostructures



Chemical Beam Epitaxy is well suited for regrowth of pre-structurered samples such as distributed feedback gratings (above)or buried heterostructure lasers. Main activities are growth of wavelength tunable laser diodes.

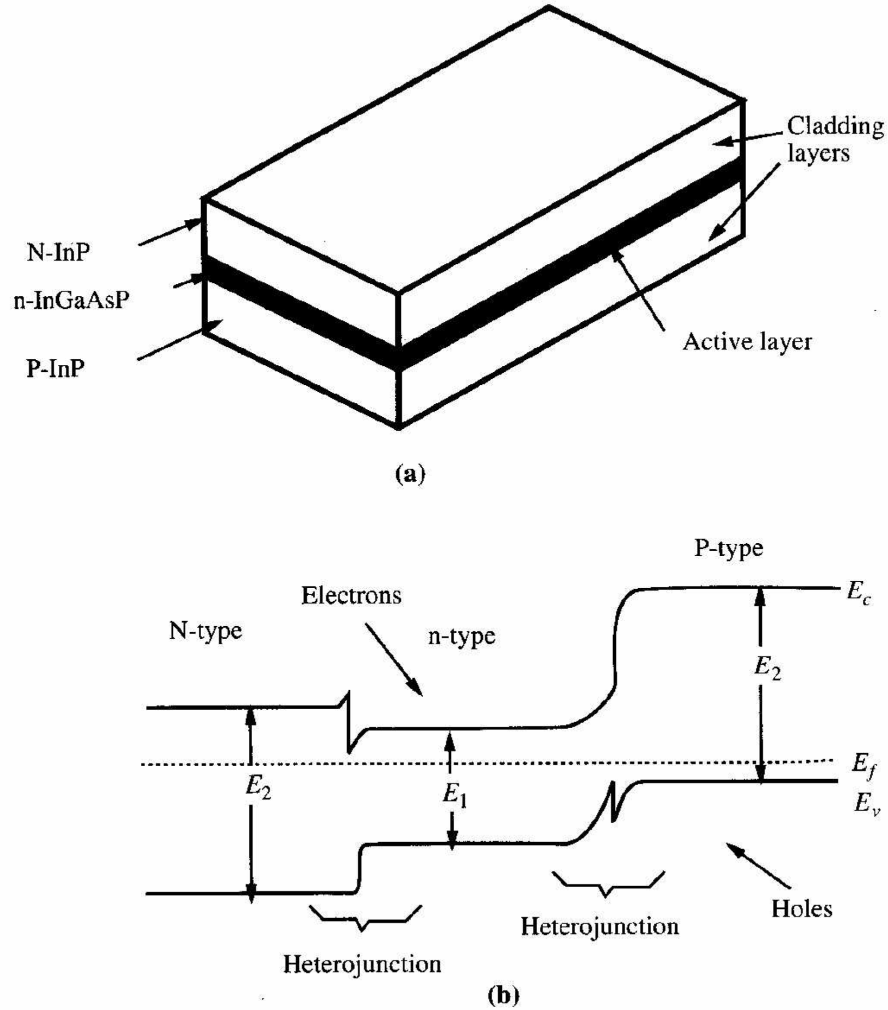


Figure 3.5 Illustration of a double heterostructure (DH): (*a*) geometrical illustration and (*b*) energy-band diagram.

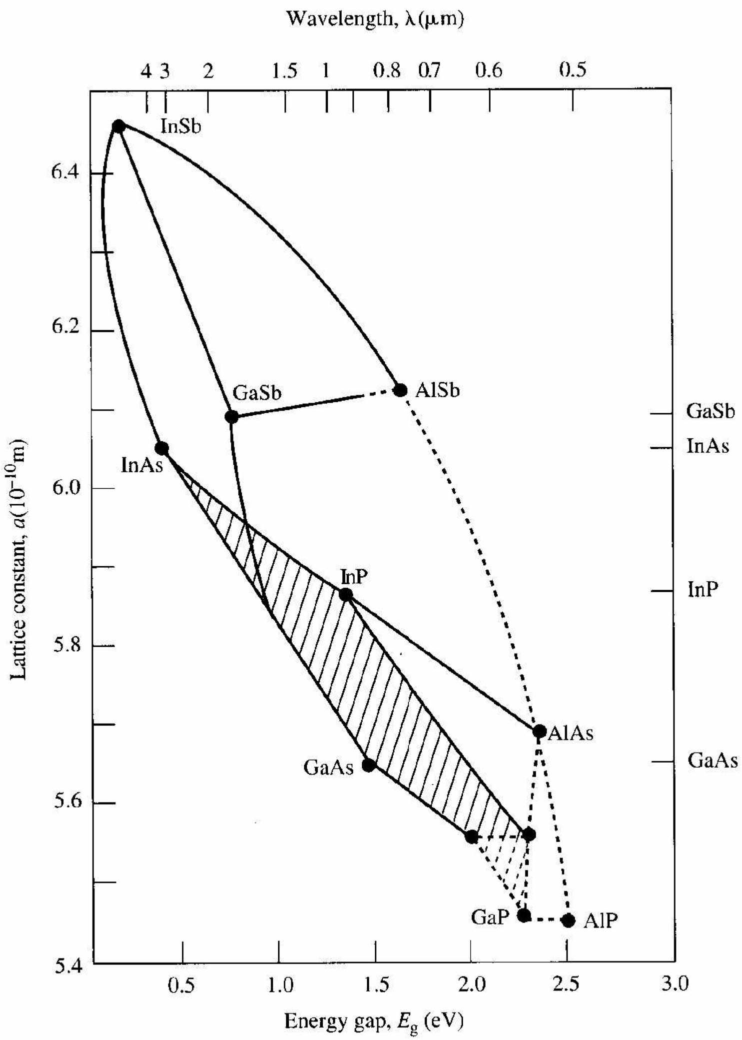
Heterostructures

- A heterostructure provides both carrier [electrons and holes] and optical confinement
- Electrons and holes are confined in the active layer because of the energy jump or block at the heterojunctions, see fig 3.5
- The photons are confined within the active layer because the refractive indices of the wider bandgap materials are smaller than that of the smaller bandgap active layer, the DH forms an optical cavity. This photon confinement is similar to that in optical fibres

Heterostructures

- When photons and carriers are confined in the same active layer, carriers can strongly interact with photons and generate large optical outputs
- Heterostructures are used in all LEDs and LDs today
- Lattice constants of materials should be closely matched, otherwise defects occur
- Figure 3.6 gives the lattice constants of the III-V compound family and their energy bandgaps
- One popular combination is InGaAsP for its small bandgap and InP for its larger bandgap

Lattice constants of III-V compounds



re 3.6 Lattice constant versus bandgap of the III–V compound family. The solid lines correspond to direct bandgap materials and the dashed lines correspond to indirect bandgap materials. The shaded area shows the quaternary compound $In_{1-x}Ga_xAs_yP_{1-y}$. The lattice match to InP occurs at $x = 0.8$ and $y = 0.65$.

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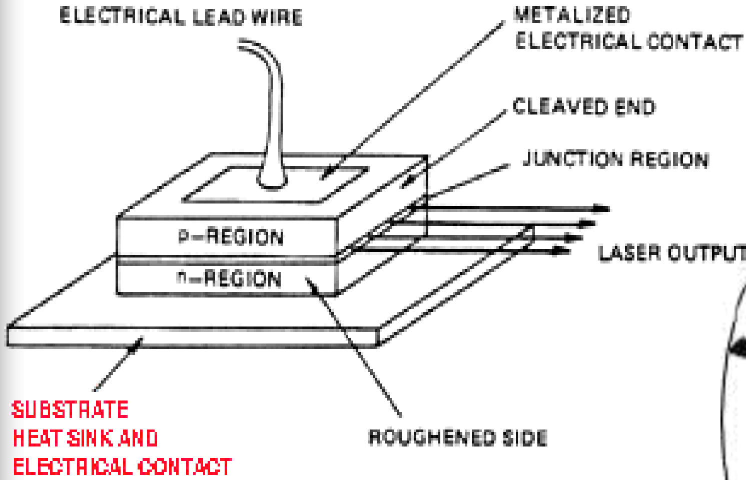
Heterostructures

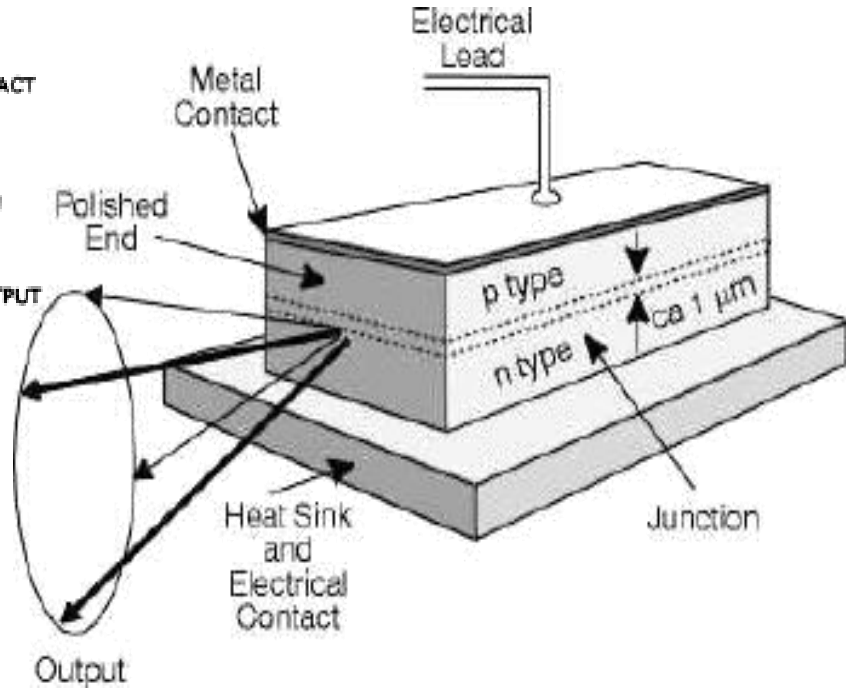
- InGaAsP/InP Heterostructure. Consider an InGaAsP laser with InP cladding
- Fig 3.6 shows that InP has a lattice constant of 5.9×10^{-10} m
- To operate the active InGaAsP layer at 1500 nm and have the same lattice constant, we need a compound $In_{1-x}Ga_xAs_yP_{1-y}$ in the shadow region

Heterostructures

- The line that connects InAs and InP represents $InAs_yP_{1-y}$ and the line that connects InAs and GaAs represents $In_{1-y}Ga_yAs$.
- Therefore, if $In_{1-y}Ga_yAs$ is used instead as the active layer, the emission wavelength is at around 2000 nm with $y \approx 0.4$

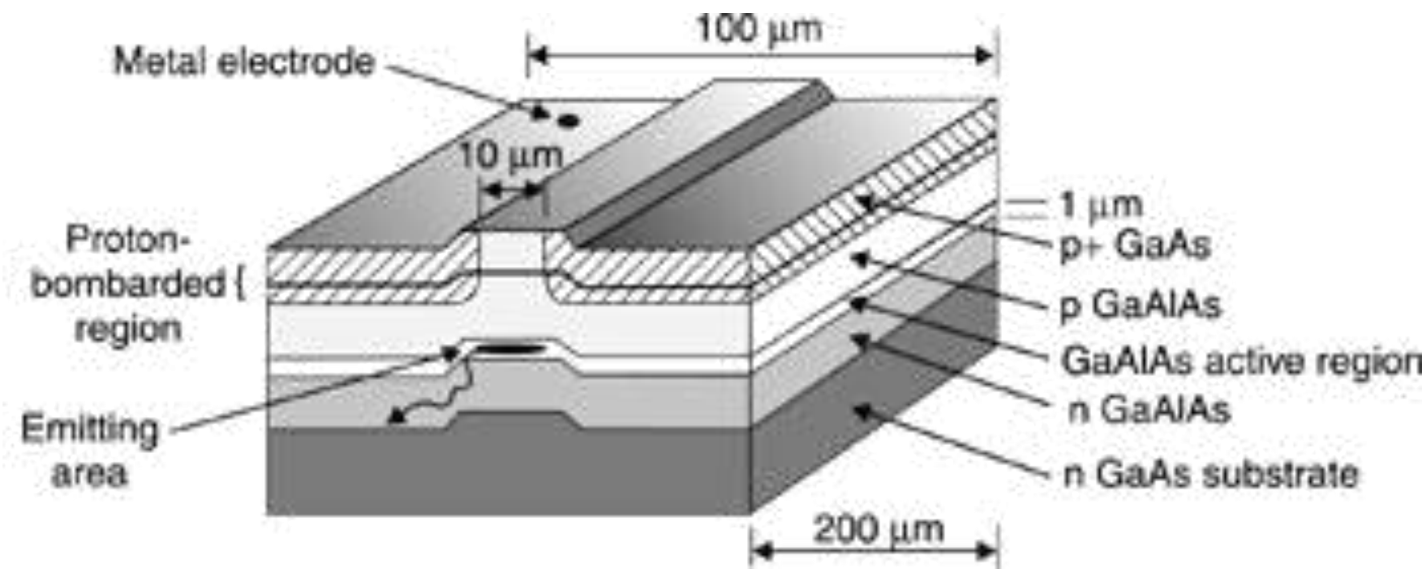
A diagram of the simplest (and earliest) type of gallium arsenide laser. GaAs cleaves easily along certain crystal planes, leaving flat parallel surfaces





Usually, the mirrors for feedback and output coupling are formed by the cleaved ends of the laser diode, with no further coating. The reflectivity at the interface between gallium arsenide and air is approximately 36%. If output is desired from only one end of the device, or if mirrors of higher reflectivity are desired to reduce the threshold for laser operation, the reflectivity may be increased by coating the surfaces with metal films. Two sides are purposely roughened to reduce reflection and prevent lasing "across" the diode cavity.

Example of a typical type of structure for a semiconductor laser diode, showing the different types of semiconductor layers commonly employed

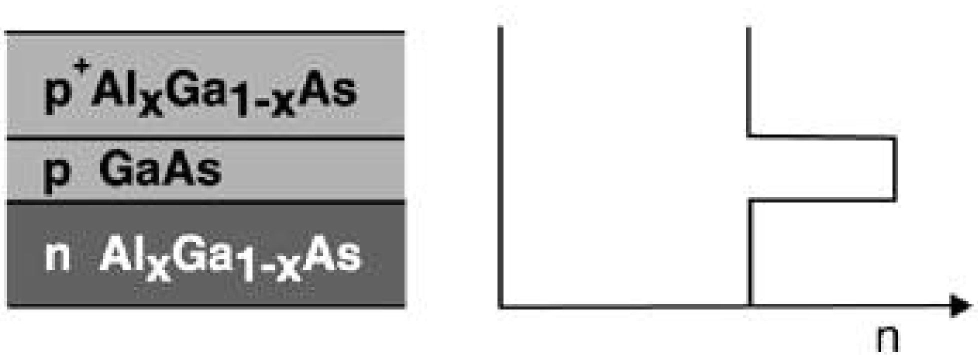


The proton-bombarded areas essentially form a stripe that confines the current and defines the area where laser operation will occur. The incorporation of a stripe, either in this fashion or by selective metallization of the surface so that the electrical contact is in the form of a stripe, is a very common feature for semiconductor lasers. The current flows only in the region where the metallization contacts the semiconductor.

The heavily doped layers are electrically conducting, facilitating making the electrical contacts. The sequence of layers AlGaAs-GaAs-AlGaAs forms what is called a double heterostructure, in which there are two changes of composition of the material as one goes through the active light-emitting region.

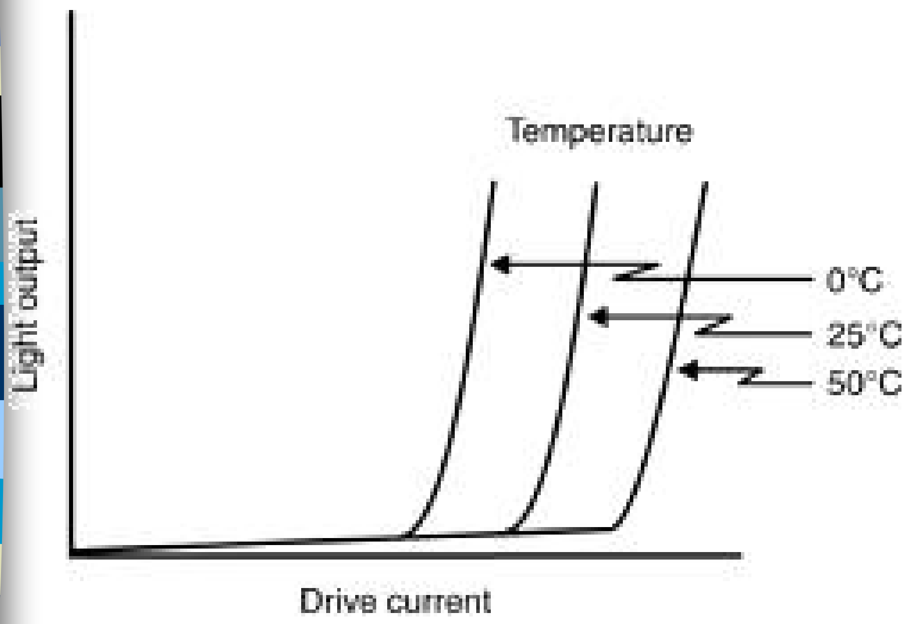
The double heterojunction (or double heterostructure), so called because there are two changes in the composition of the material as one goes through the junction. This confines the light from both sides by waveguiding effects and reduces the current requirements considerably.

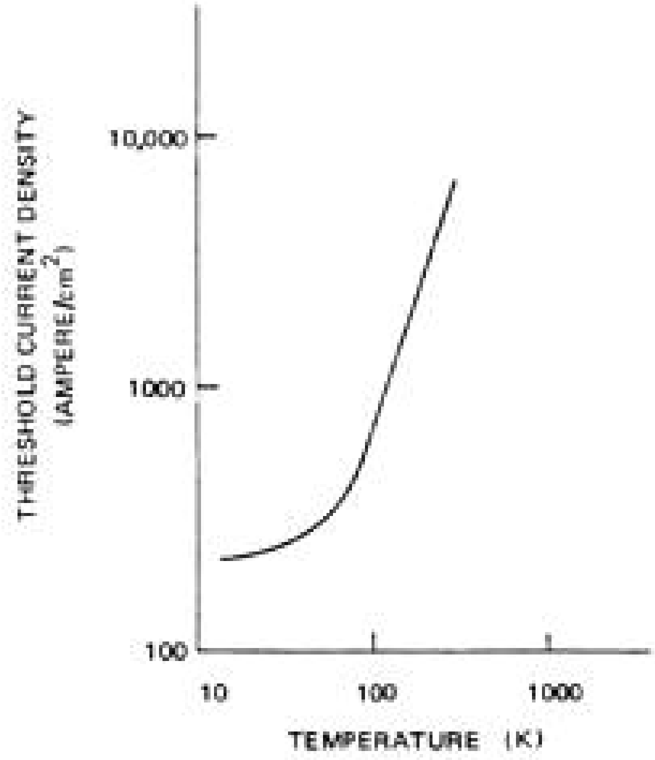
Structure and index of refraction for the aluminum gallium arsenide system. Double heterojunction



Gallium Arsenide Laser

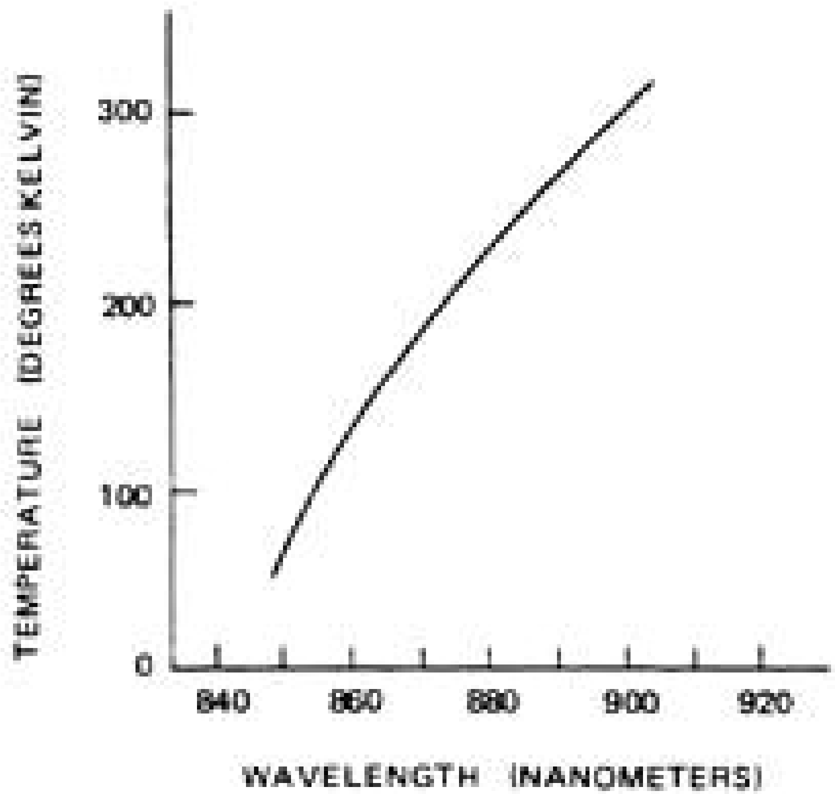
a) Schematic sketch of the output of a typical laser diode as a function of drive current for three different operating temperatures.
b) Temperature dependence of threshold current.





Temperature Dependence of Wavelength

Temperature dependence of lasing wavelength



Gallium arsenide lasers emit radiation in the near infrared portion of the spectrum. The exact wavelength depends on the temperature at which the laser is operated. This is shown in the graph which gives the wavelength of a gallium arsenide laser as a function of temperature. The lifetime decreases exponentially with increasing temperature, the laser must be in good thermal contact with a heat sink capable of dissipating the thermal load generated by the laser.

Light-emitting diodes

- Light emitting diodes are semiconductor diodes that emit incoherent light
- Incoherent light is an optical carrier with a rapidly varying random phase and a broad spectrum
- This random phase results from independent EHRs
- Figure 3.7 illustrates a typical light spectrum of a GaAlAs LED. The line width is of the order of 100 nm with a central wavelength around 870 nm

Linewidth

- A common definition of linewidth is called full-width half-maximum (FWHM), which is the width between two 50% points of the peak intensity
- The FWHM of the line width in figure 3.7 is approximately 30 nm
- Relationship between linewidth and spectrum width

$$\lambda f = c$$

Linewidth

- Taking the total derivative of: $\lambda f = c$

$$f\partial\lambda + \lambda\partial f = 0.$$

- For a given linewidth $\Delta\lambda$, we thus have

$$\boxed{\frac{|\Delta\lambda|}{\lambda} = \frac{|\Delta f|}{f}, |\Delta\lambda| = c\frac{|\Delta f|}{f^2}, |\Delta f| = c\frac{|\Delta\lambda|}{\lambda^2}}$$

- Where Δf is the corresponding spectral width

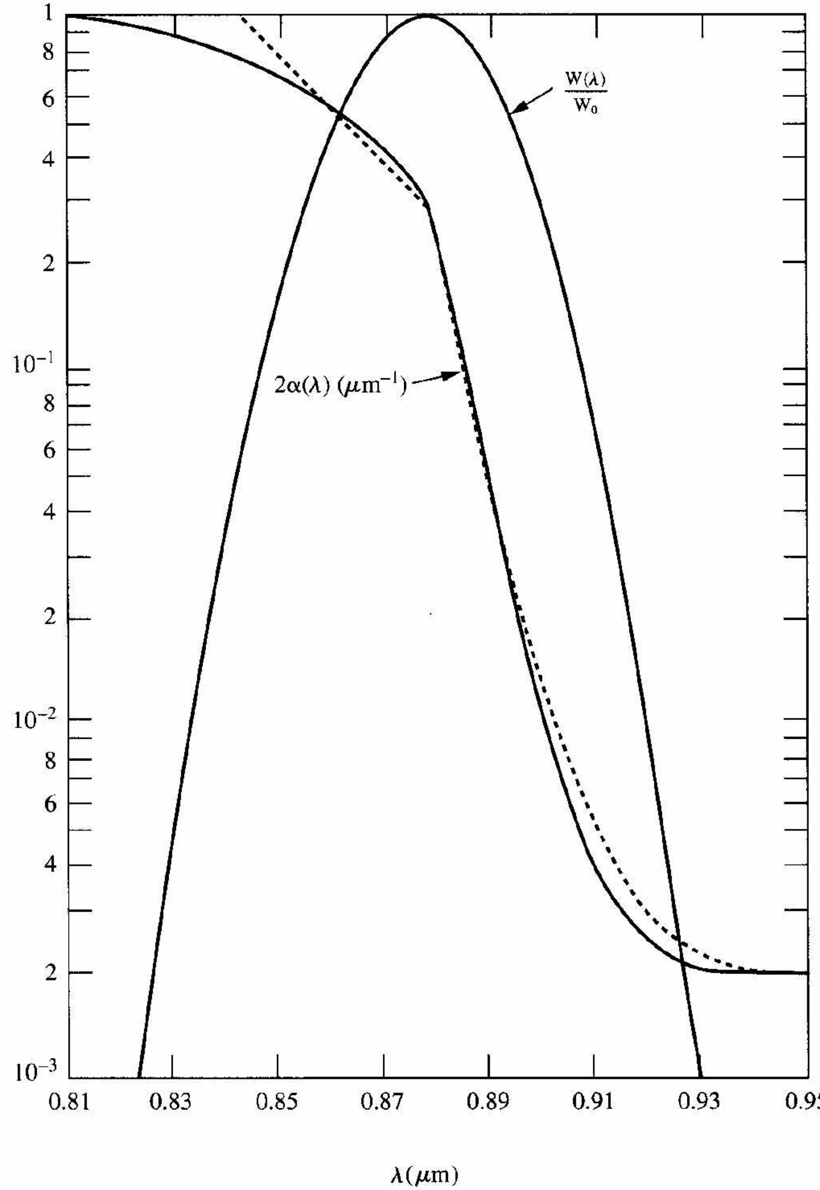


Figure 3.7 Linewidth of an LED.

SOURCE: Reprinted, by permission, from Marcuse, "LED Fundamentals," p. 819 [18]. © 1977 by IEEE.

Spectral width and linewidth conversion

- For the FWHM linewidth of 30 nm of the AlGaAs LED in fig 3.7, the FWHM spectrum width is
- $\Delta f = f\Delta\lambda / \lambda = c / \lambda^2 \, \Delta\lambda = 12$ THz
- This is a large spectrum bandwidth when compared to most baseband signal bandwidths
- It is impossible to perform phase or frequency modulation using LEDs
- Only amplitude modulation is used for LEDs

Spectrum Width

- Depends on the material, temperature, doping level and light coupling structure
- For AlGaAs devices, the FWHM spectrum width of LEDs is about 2kT/h,
- For InGaAsP devices, it is about $\Delta f = 3kT/h$
- As the doping level increases, the linewidth also increases
- Temperature dependence of linewidth for AlGaAs LED operating at 300K
- $\Delta f = 2kT/h = 2 \times 1.38 \times 10^{-23} \times 300 / 6.62 \times 10^{-34}$
- $\Delta f = 2kT/h = 12.4$ THz

Light Coupling Structure

- The spectrum width also depends on the light coupling structure of the LED
- Two different light coupling structures:
  - Surface emitting, fig 3.8
  - Edge emitting, fig 3.9
- Because of self-absorption along the length of the active layer, edge emitting LEDs have smaller linewidths than surface emitting diodes

Light Coupling Structure

- The output light has an angle of around 30 degrees vertical to the active layer
- Surface emitting LEDs have a large coupling area and it is easier to interface them with fibres, self aligned
- They are more easily cooled because the heat sink is close to the active layer

Surface emitting LED

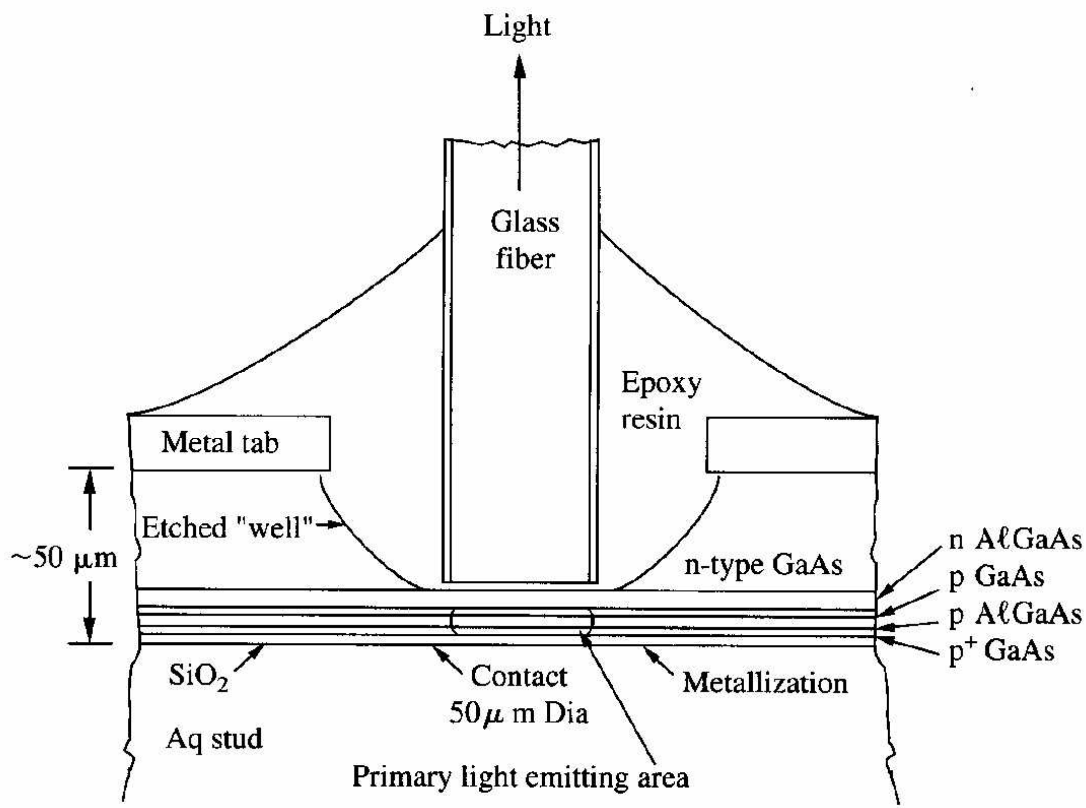


Figure 3.8 Illustration of a surface-emitting diode.

SOURCE: Reprinted, by permission, from Saul, Lee, and Barrus, Chapter 5 "Light Emitting Diode Devices Design," p.197, of Semiconductor & Semimetals, vol. 22, Part C, edited by Tsang[19]. © by Academic Press, 1985.

Edge emitting LED

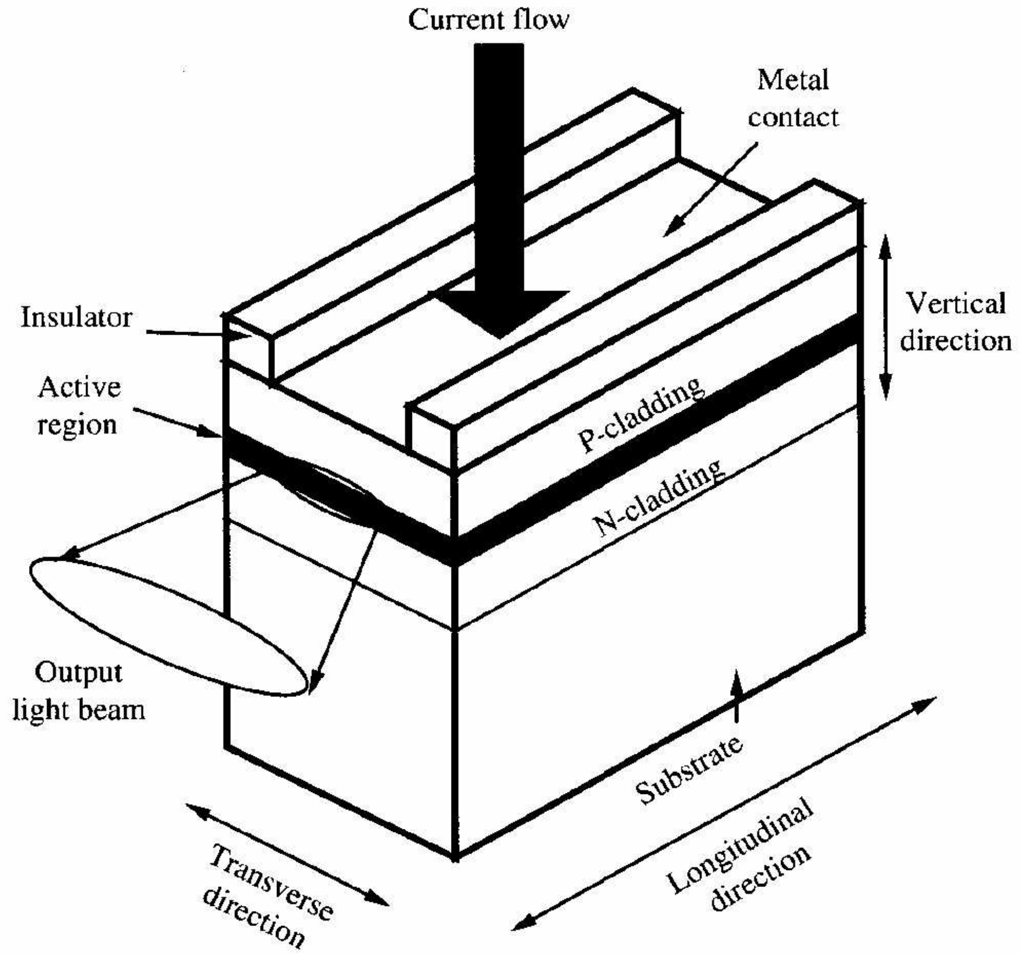


Figure 3.9 Illustration of an edge-emitting diode.

Light Emitting Diode Color Variations

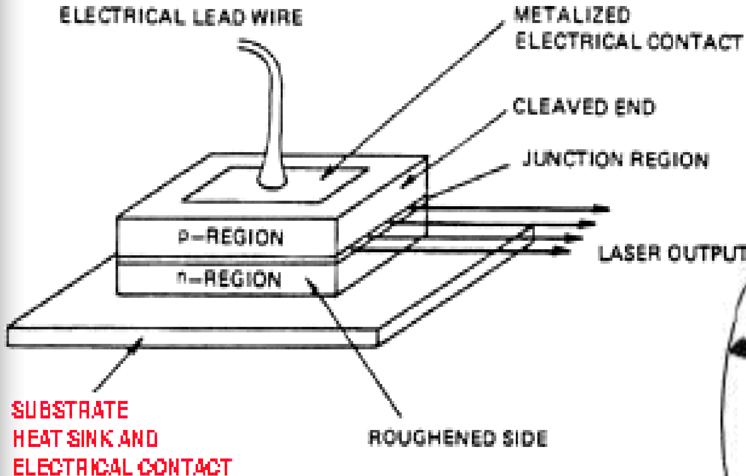
Colour Name	Wavelength (Nanometers)	Semiconductor Composition
Infrared	880	GaAlAs/GaAs
Ultra Red	660	GaAlAs/GaAlAs
Super Red	633	AlGaInP
Super Orange	612	AlGaInP
Orange	605	GaAsP/GaP
Yellow	585	GaAsP/GaP
Incandescent White	4500K (CT)	InGaN/SiC
Pale White	6500K (CT)	InGaN/SiC
Cool White	8000K (CT)	InGaN/SiC
Pure Green	555	GaP/GaP
Super Blue	470	GaN/SiC
Blue Violet	430	GaN/SiC
Ultraviolet	395	InGaN/SiC

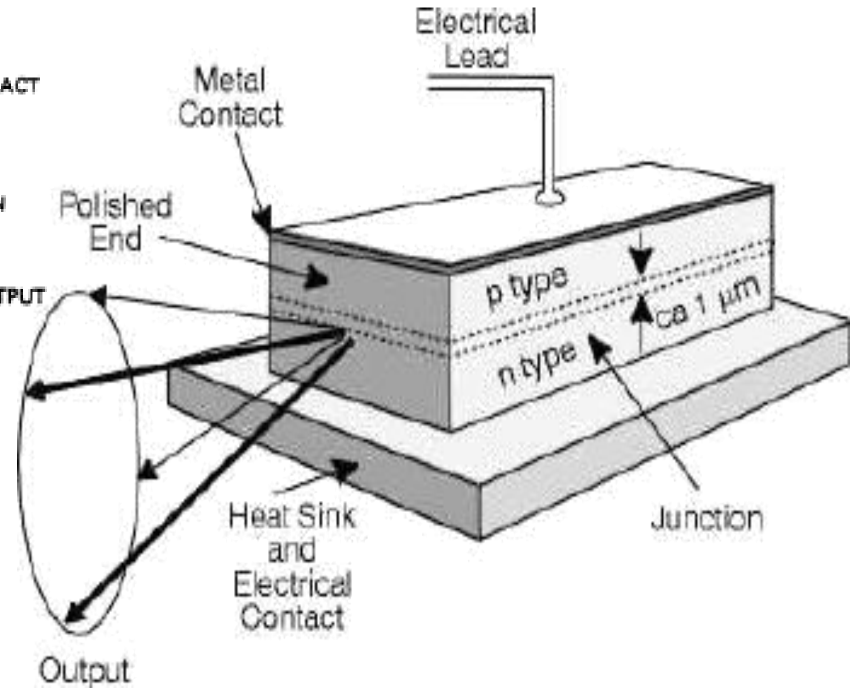
Laser Diodes

- A basic laser diode structure is similar to that of the edge-emitting LED in figure 3.9
- By adding an additional structure for transverse photon confinement, a coherent carrier close to what is expressed in equation 3.1 can be generated

$$c(t) = A\cos(\omega_c t + \phi) \quad \ldots\ldots\ldots 3.1$$

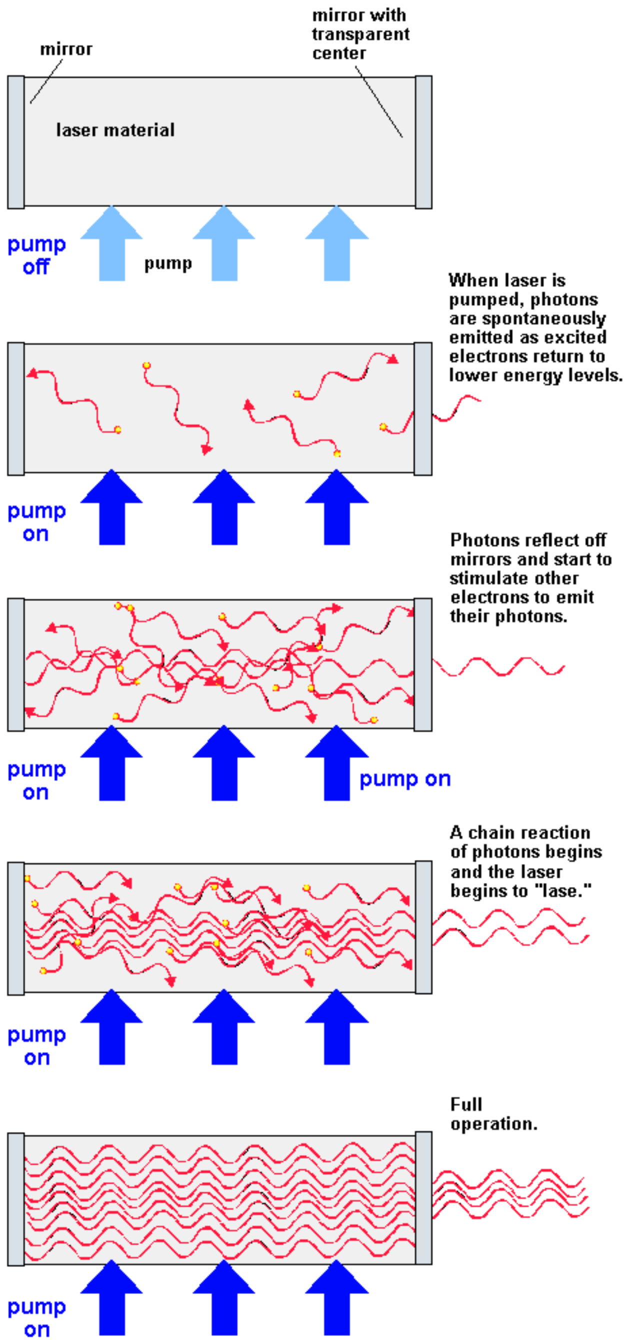
A diagram of the simplest (and earliest) type of gallium arsenide laser. GaAs cleaves easily along certain crystal planes, leaving flat parallel surfaces





Usually, the mirrors for feedback and output coupling are formed by the cleaved ends of the laser diode, with no further coating. The reflectivity at the interface between gallium arsenide and air is approximately 36%. If output is desired from only one end of the device, or if mirrors of higher reflectivity are desired to reduce the threshold for laser operation, the reflectivity may be increased by coating the surfaces with metal films. Two sides are purposely roughened to reduce reflection and prevent lasing "across" the diode cavity.

Spontaneous then Stimulated emission



Laser Diodes

- The energy system of semiconductor lasers is shown in Figure 3.11, where E_c is the conduction band energy and E_ν is the valence band energy
- External pumping is achieved by current injection, which supplies electrons and holes to their conduction band and valence band, respectively
- When electrons and holes recombine,as in LEDs, they generate photons

Carrier recombination and photon emission in a LD

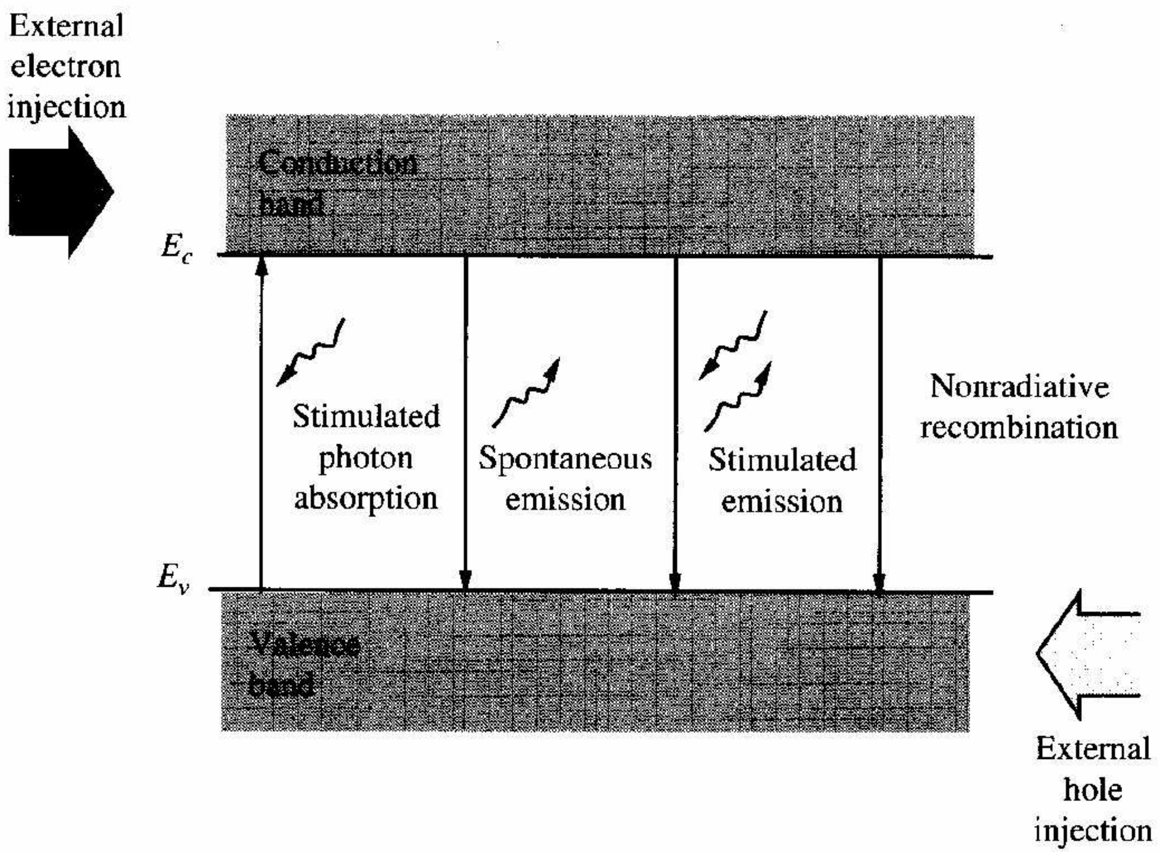


Figure 3.11 Carrier recombination and photon emission in a semiconductor laser diode.

Light amplification

- When a carrier is pumped to the upper state, it can come back to the ground state either spontaneously or by stimulation:
  - Spontaneous emission – random phase and frequency – incoherent light
  - Stimulated emission – same phase and frequency as the stimulating photons – coherent light

Light amplification

- Electron hole pairs (EHP) are generated by external current injection and stimulated photon absorption.
- They can later recombine either spontaneously or by stimulated emission
- Because of leaky current at the p-n junction, there is also non-radiative carrier recombination in semiconductors

Cavity Confinement

- As shown in figure 3.12, a laser cavity is a rectangular cavity of six walls, all of which should provide good photon and carrier confinement to reduce cavity loss.
- Two are at the longitudinal ends of the cavity which need to couple light out
- Two are the heterojunctions which achieve both carrier and photon confinement from the energy bandgap and refractive index, respectively.
- Therefore the only additional confinement needed is at the transverse sides of the junction plane

Laser Cavity

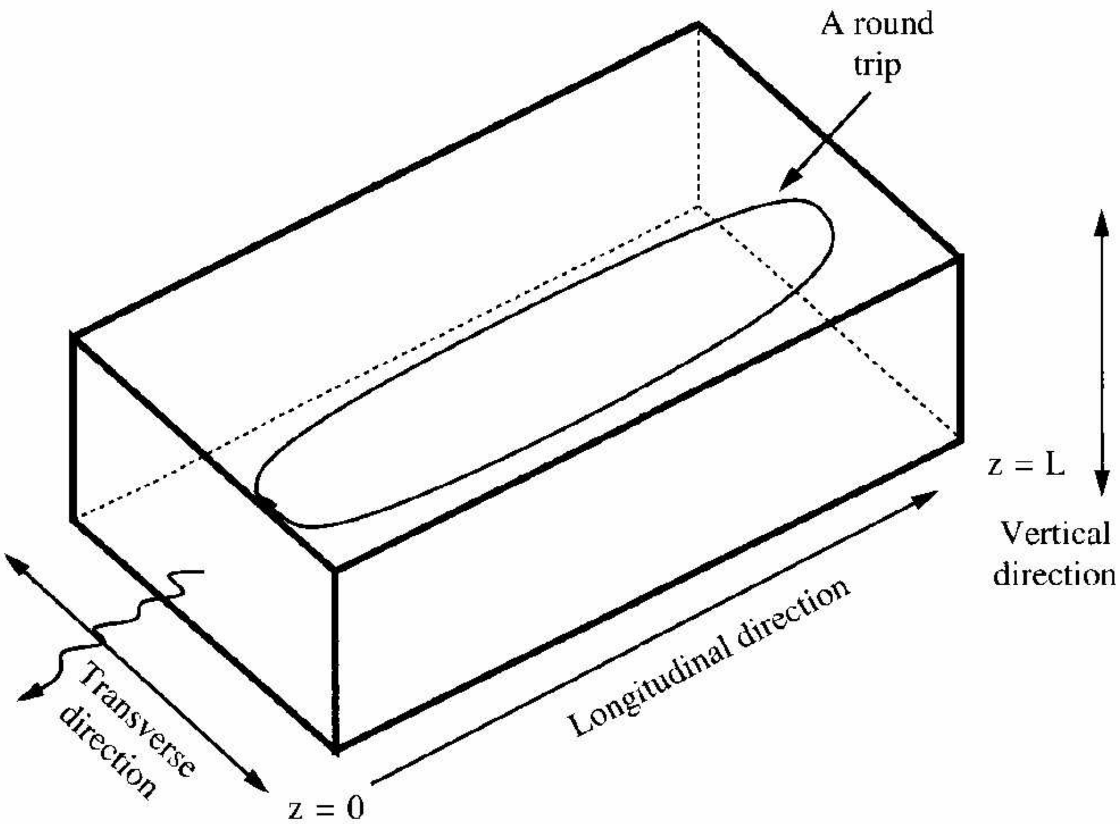


Figure 3.12 Illustration of a laser cavity.

Cavity Confinement

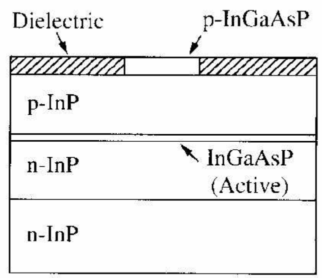
- To provide the confinement at the two transverse sides, three structures have been used:
- 1) Gain guided
- 2) Weakly index guided
- 3) Strongly index-guided lasers

Objective: High output power; Low threshold current; Small linewidth; Large modulation bandwidth; Low noise; Good tuneability

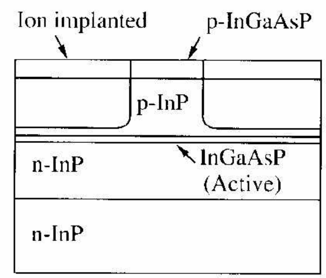
Gain Guided Lasers

- A gain guided laser has a structure that confines transverse current flow
- Three types of gain guided laser diodes are shown in figure 3.13
- The oxide strip laser is the same basic heterostructure laser shown in figure 3.9 and uses the P-contact on top to define the current flow region. Therefore little current flows under the silicon dioxide dielectric layer

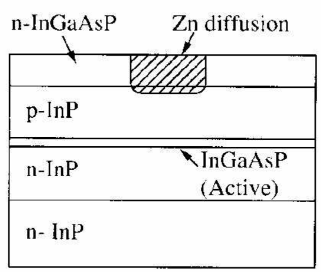
Three different gain guided structures



(a) Oxide-stripe laser



(b) Proton- or deuteron-stripe laser



(c) Junction-stripe laser

Figure 3.13 Three different gain-guided index structures.

SOURCE: Reprinted, by permission, from Dutta Chapter 9 of *Optical Fiber Transmission* edited by E.E. Basch "Optical Sources," p. 275, Figure 10 [28]. © 1987 by McGraw-Hill.

[2]Transverse modes are different sets of wavefunctions that satisfy the wave equations in the cavity. Similar to longitudinal modes that are determined by the longitudinal direction of the cavity (see Section 3.6), transverse modes are determined by the transverse current distribution or gain in the cavity. Chapter 4 discusses the concept of the waveguide and resonator modes in more detail.

Gain Guided Lasers

- Second type uses either a proton stripe or a deuteron stripe to create a high resistivity region by which the transverse current flow is restricted
- The third type has a junction stripe where most current flows through the P-type area converted by zinc diffusion and little current flows under the reversed-bias n-p junction
- In these gain guided lasers, there is no physical confinement for photons on the two transverse sides.
- In fact the high current region has a lower refractive index and poor optical confinement
- In addition, there is no physical confinement for carriers except for the proton or deuteron – type lasers.

Gain Guided Lasers

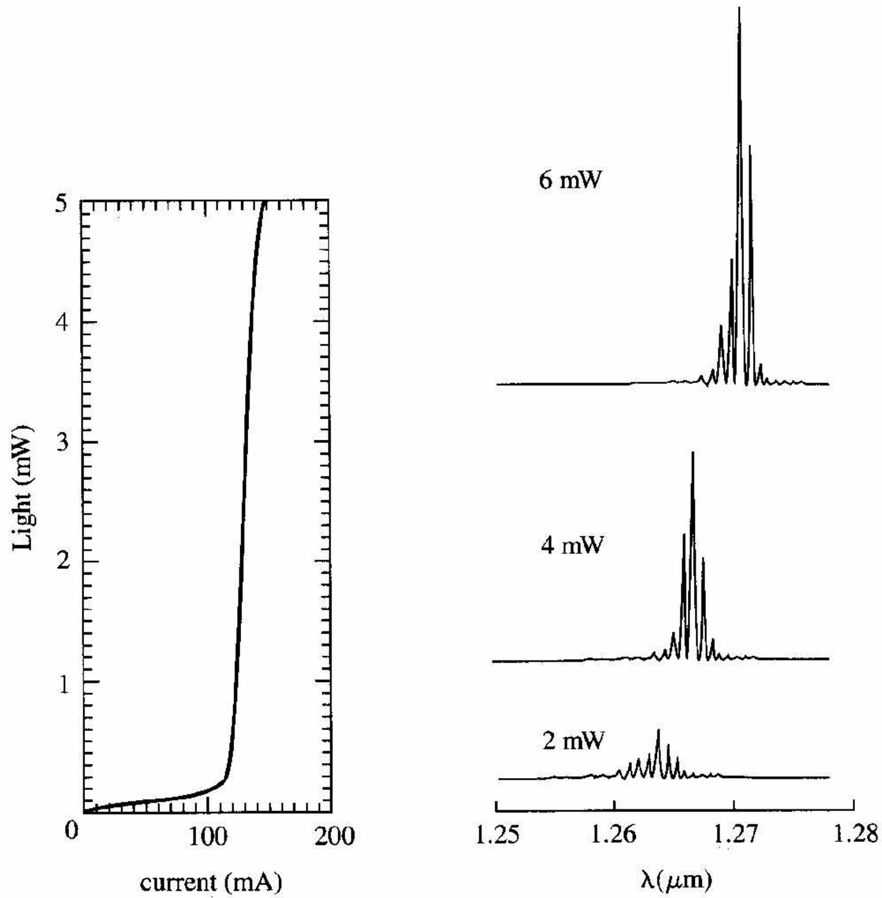


Figure 3.14 (a) Light power versus input current; (b) output optical spectrum.

SOURCE: Reprinted, by permission, from Schwartz et al., "Stripe Geometry," p. 841 [26]. © 1984 by IEEE.

Gain-guided lasers

- Gain guided lasers do not have a strong transverse confinement and thus have a large threshold current
- As illustrated in figure 3.14 the threshold current is around 100 mA
- Because of the weak transverse confinement, there can be several transverse modes
- As the driving current increases, the current density distribution changes in the active layer, which results in shifts in transverse modes

Weakly Index-guided lasers

- To provide better confinement, especially for photons, index difference must be introduced on the two transverse sides
- A waveguide structure of different material is grown below or above the active layer. This provides an index change up to 1% at the two transverse sides
- As shown in fig 3.15, when a waveguide (P-type InP) is grown above the active layer (InGaAsP), it is called a **ridge waveguide** index-guided diode. When a waveguide is grown below the active layer (N-type InP) it is called a **rib waveguide** diode
- With index-guiding, carriers and photons are better guided. Therefore the threshold current is smaller, typically from 40 to 60 mA

Weakly Index-guided lasers

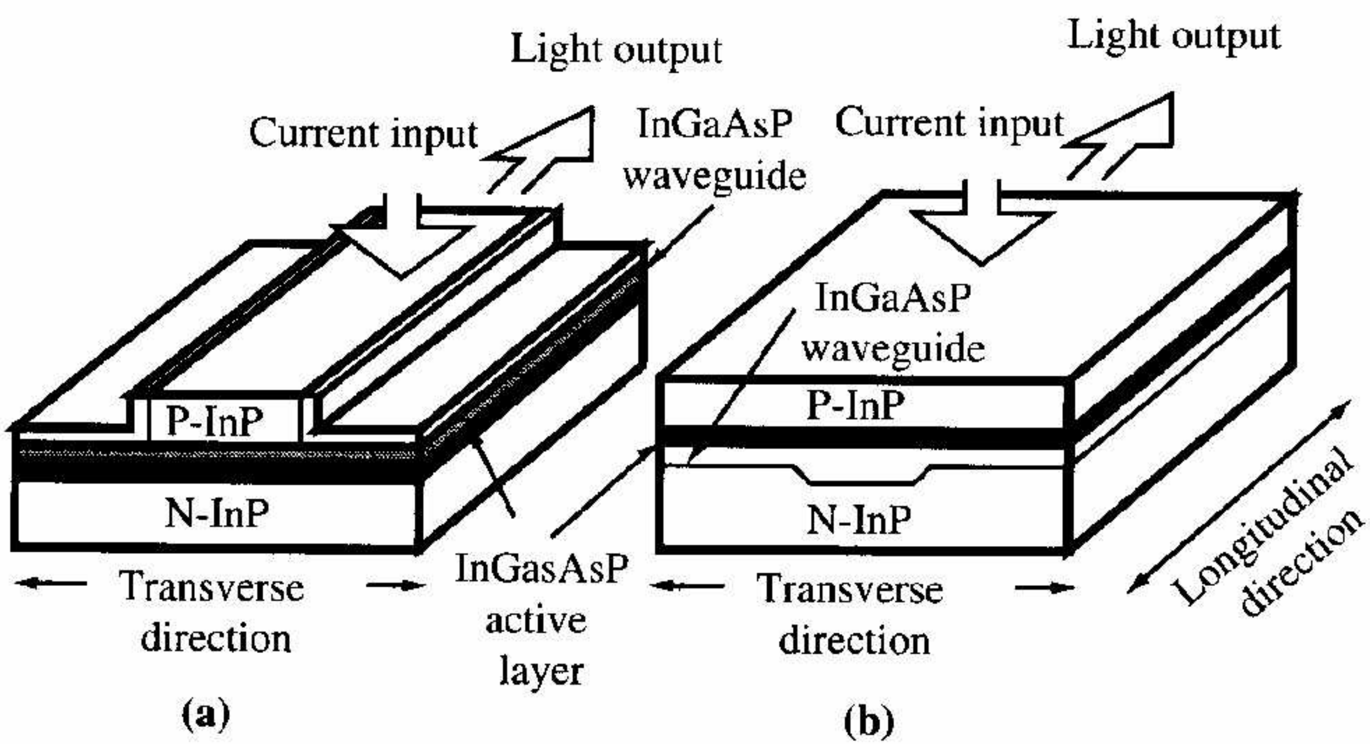


Figure 3.15 Illustrations of (*a*) ridge waveguide and (*b*) rib waveguide weak index-guiding.

Strongly Index-guided lasers

- Instead of adding a waveguide structure below or above the active layer, strongly index-guided lasers have a physical structure on the two transverse sides of the active layer to introduce an index change of around 0.2
- Two important strongly index-guided lasers are illustrated in figure 3.16
- They are called buried-heterostructure (BH) lasers
- Strongly index-guided lasers introduce another two heterojunctions on the two transverse sides to provide both carrier and photon confinement, the threshold current at room temperature can be as low as 10mA

Strongly Index-guided lasers

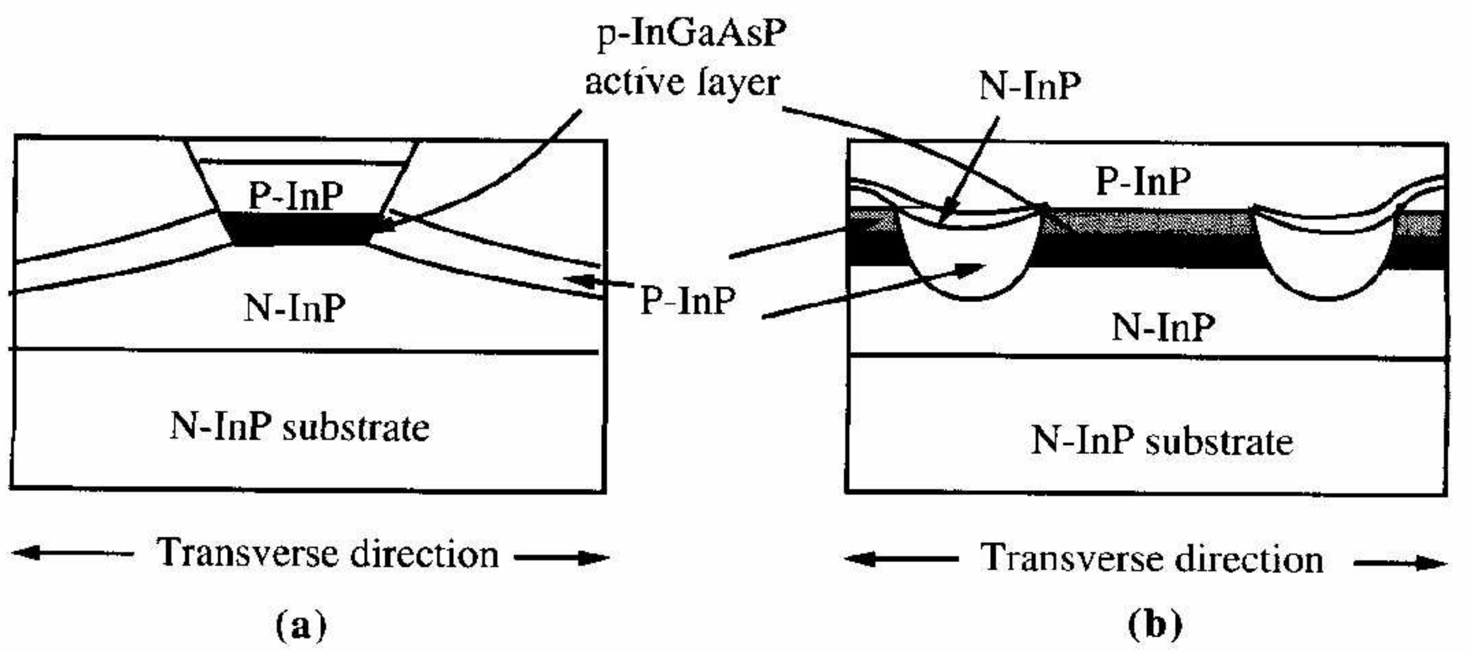


Figure 3.16 Illustrations of buried heterostructures: (*a*) etched-mesa (EM-BH) and (*b*) double-channel-plannar (DCP-BH).

Fabry-Perot Laser Diodes

- With the cavity confinement discussed above, a basic LD that has a rectangular cavity has a Fabry-Perot resonator and is thus called an FP LD
- When photons are reflected back and forth between the two FP cavity ends, they experience both gain and loss
- The gain comes from the stimulated emission and the loss comes from the medium absorption and partial reflection from the two cavity ends
- From this condition, the required gain from stimulated emission can be derived

Laser Cavity

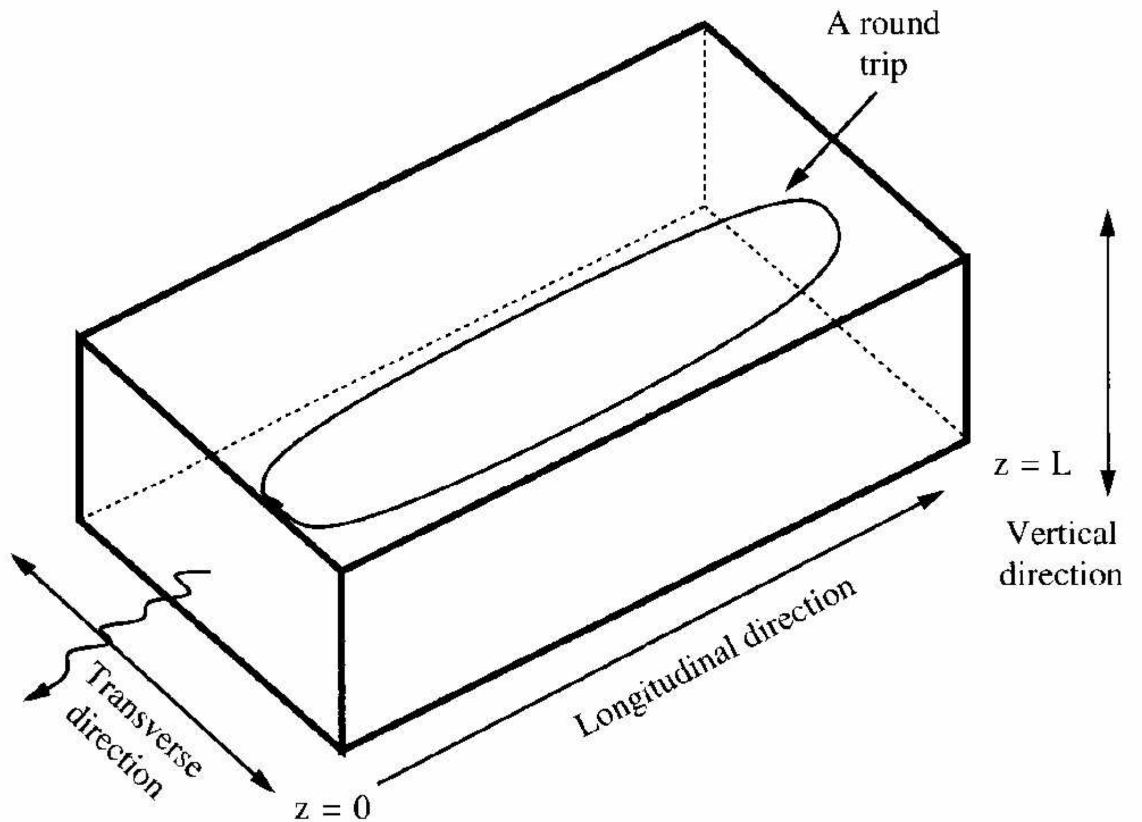


Figure 3.12 Illustration of a laser cavity.

Fabry-Perot Laser Diodes

- Assume the wavefunction of a lightwave is a scalar and has a value A at point z = 0. From figure 3.12, the wave travelling to the right can be expressed as:

$$E^{+}(z) = Ae^{(j\beta_z - \alpha/2 + g/2)z}$$

- Where β_z is the propagation constant along the z-axis and α and g are the distributed medium loss and gain, respectively. The time dependence factor e^{-jwt} is dropped as it is irrelevant and the power of the travelling wave is $e^{(g-\alpha)z}$.
- At z = L, the wave function has the value $Ae^{(j\beta-\alpha+g)L}$.
- Assuming the cavity end on the right has a reflection coefficient of r_2 , the reflected wave travelling to the left can be written as:

$$E^{-}(z) = r_2 Ae^{(j\beta_z - \alpha/2 + g/2)(2L - z)}.$$

Fabry-Perot Laser Diodes

- The round trip is complete after the left travelling wave is reflected back by the left mirror with reflection coefficient r_1 . Therefore the conditions of a unit round trip gain in the steady state are:

$$r_1 r_2 e^{(g-\alpha)(L)} = 1 \qquad \text{.....3.9}$$

- And

$$2L\beta_z = 2m\pi \qquad \text{.....3.10}$$

- Where *m* is an integer. Equation (3.9) can be expressed as:

Where α_m accounts for the reflection loss at the cavity ends

$$\boxed{g = \alpha - \frac{1}{L} \times \ln(r_1 r_2) = \alpha + \alpha_m = \alpha_{tot}} \qquad \text{...3.11}$$

Fabry-Perot Laser Diodes

- Equation (3.11) is the gain-loss condition at the steady state and
- Equation (3.10) is the phase condition for the laser wavelength
- This second condition is the basis for the longitudinal modes
- The gain-loss condition in equation (3.11) is only applicable to the steady state
- Before the laser reaches the steady state, the gain is greater than the loss

Fabry-Perot Laser Diodes

- A steady state is reached where the stimulated emission rate is in equilibrium with the carrier supply or generation rate.
- Therefore, the output power is determined by the injected current supply.

Longitudinal Modes

$$2L\beta_z = 2m\pi \qquad \text{.....3.10}$$

- Substituting $\beta_z = 2\pi n/\lambda$
- Into the round trip condition equation 3.10 we get

$$\lambda_m = \frac{2Ln}{m} \qquad \text{.......3.14}$$

- Where n is the refractive index of the gain medium and λ_m is the mth longitudinal mode. When m is a large integer, the longitudinal mode separation between λ_m and λ_{m+1} is

$$\boxed{\Delta\lambda_{long} = \lambda_m - \lambda_{m+1} = 2Ln\left\{\frac{1}{m} - \frac{1}{(m+1)}\right\} \approx 2Ln\frac{1}{m^2} = \frac{\lambda^2}{2Ln}.} \qquad 3.15$$

Longitudinal Modes

- When carriers are generated by an externally injected current, depending on their energy distributions in the conduction and valence bands, they contribute to stimulated emissions at different longitudinal modes.
- The distribution of this emission contribution determines the gain distribution, which is centred around a frequency slightly higher than that of the energy bandgap.

Longitudinal Modes

- Figure 3.17 illustrates a typical gain profile of a laser diode

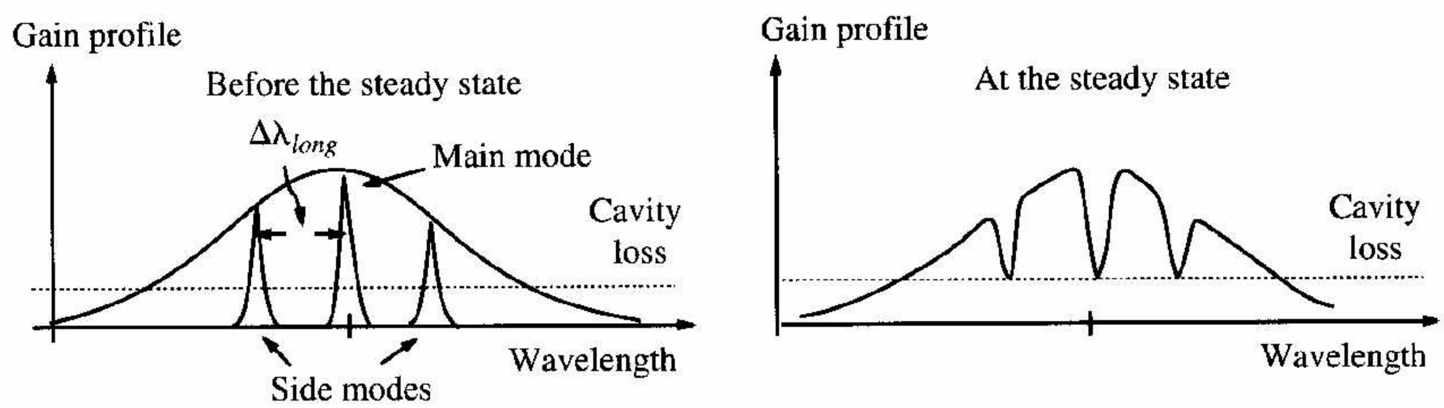


Figure 3.17 Illustration of gain profile and possible longitudinal modes.

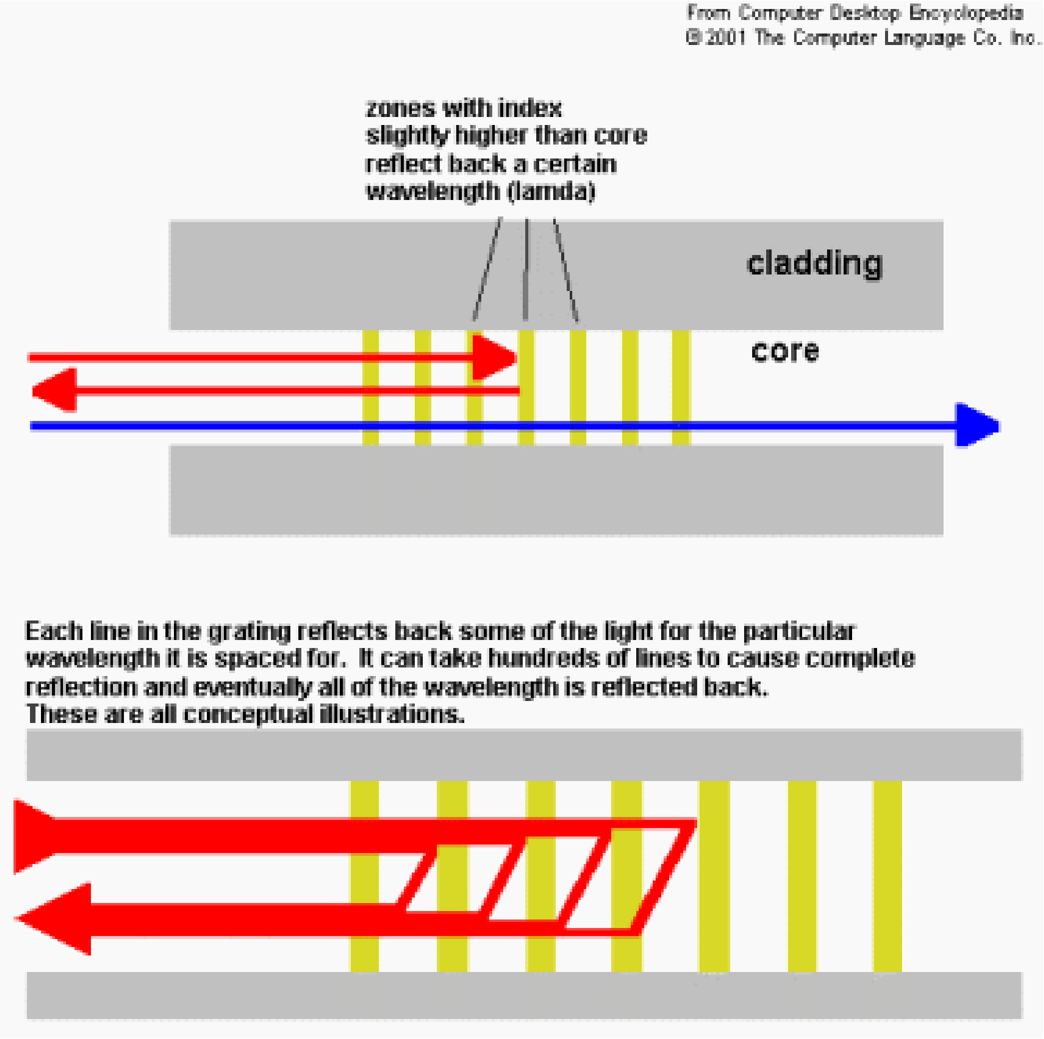
Longitudinal Modes

- A gaussian or parabolic gain profile is generally assumed in modelling
- As illustrated, only those longitudinal modes with initial gains higher than the cavity loss can exist.
- The main mode is not necessarily at the peak of the gain profile

Single Longitudinal Mode Laser Diodes

- FP laser diodes generate undesirable multiple longitudinal modes
- Important single mode lasers include:
  - – Distributed feedback lasers (DFB)
  - – Distributed Bragg reflector lasers (DBR)
  - – Cleaved-coupled-cavity lasers (C^3)
  - – Quantum Well Lasers

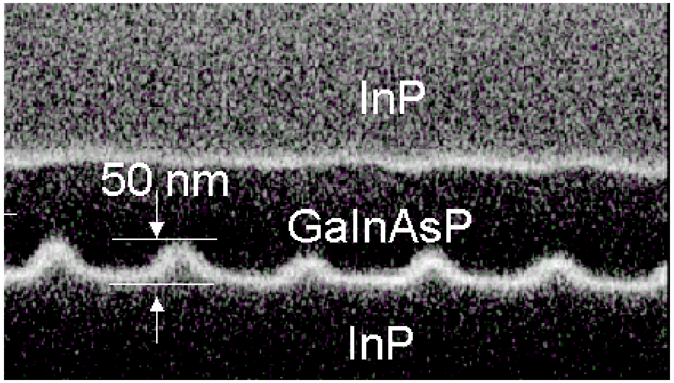
Bragg Grating



DFB Lasers

- DFB lasers use Bragg reflection to suppress undesirable modes
- Figure 3.18 shows the periodic structure inside the cavity with the period equal to Λ
- Because of the periodic structure, a forward travelling wave has interference with a backward travelling wave
- To have constructive interference, the round trip phase change over one period should be $2\pi m$, where m is an integer and is called the order of the Bragg diffraction

DFB Lasers



Chemical Beam Epitaxy is well suited for regrowth of pre-structurered samples such as distributed feedback gratings (above)or buried heterostructure lasers. Main activities are growth of wavelength tunable laser diodes.

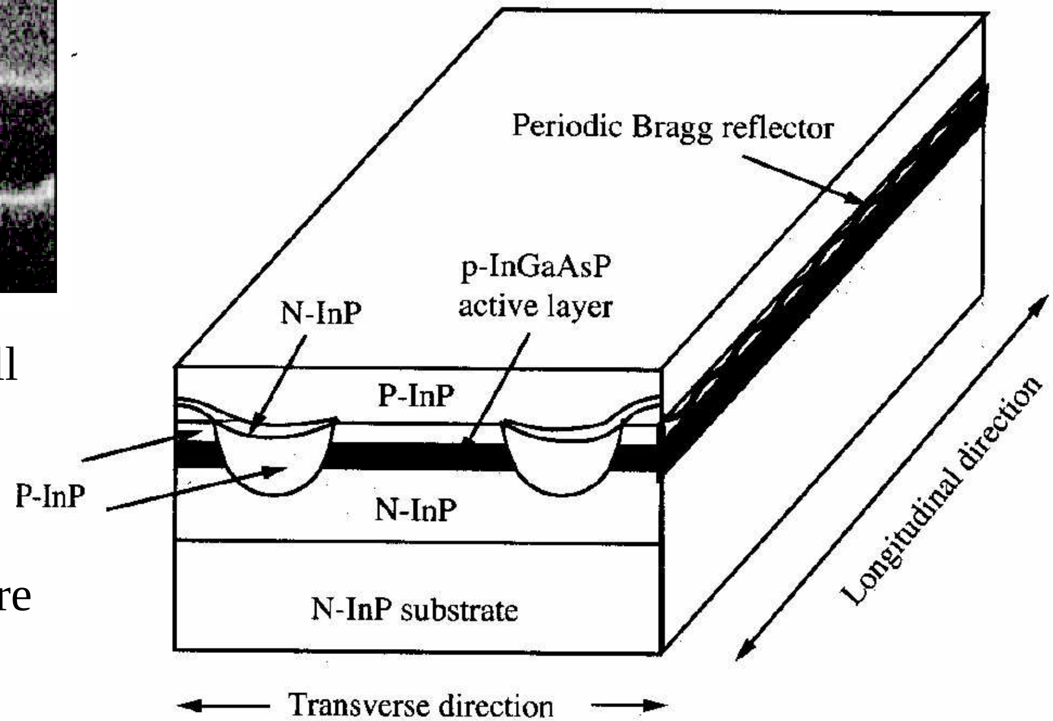


Figure 3.18 Illustration of a buried-heterostructure DFB LD.

DFB laser

- With m = 1, the first order Bragg wavelength is:
- $2\pi = 2\Lambda\, 2\pi n / \lambda_B$ or
- $\lambda_B = 2\Lambda n$ ……………….3.16
- Therefore, the period of the periodic structure determines the wavelength of the single mode light output.
- In reality, a periodic DFB structure generates two main modes with symmetric offsets from the Bragg wavelength

DFB Laser

- To generate only one mode at the Bragg wavelength, a phase shift of $\lambda/4$ can be used to remove the symmetry.
- Figure 3.19 shows the periodic structure has a phase discontinuity of $\pi/2$ at the middle, which gives an equivalent of $\lambda/4$ phase shift.

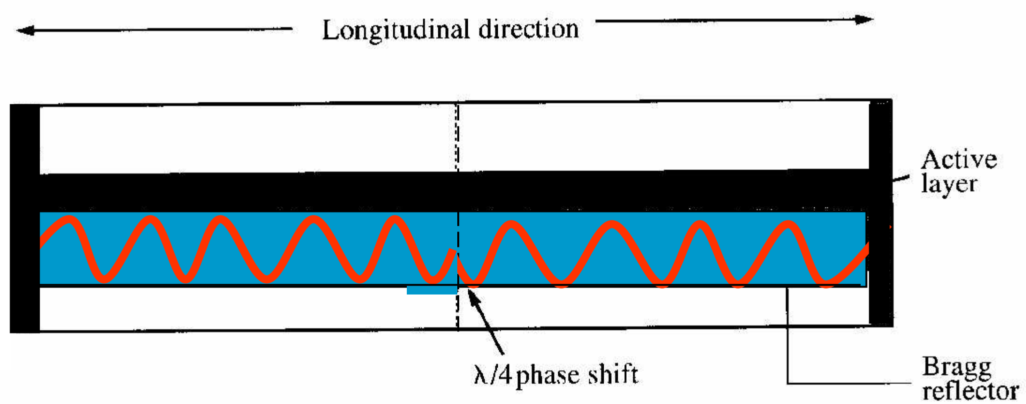


Figure 3.19 Illustration of a $\lambda/4$ phase-shift DFB LD.

DBR Lasers

- DBR lasers use the same Bragg reflection principle to generate only one longitudinal mode.
- The difference between DBR and DFB lasers is that DBR lasers have the diffraction structure outside the laser cavity, as shown in figure 3.20
- With this arrangement, the laser control (laser cavity) and the frequency control (Bragg reflection cavity) can be done separately.

DBR Laser

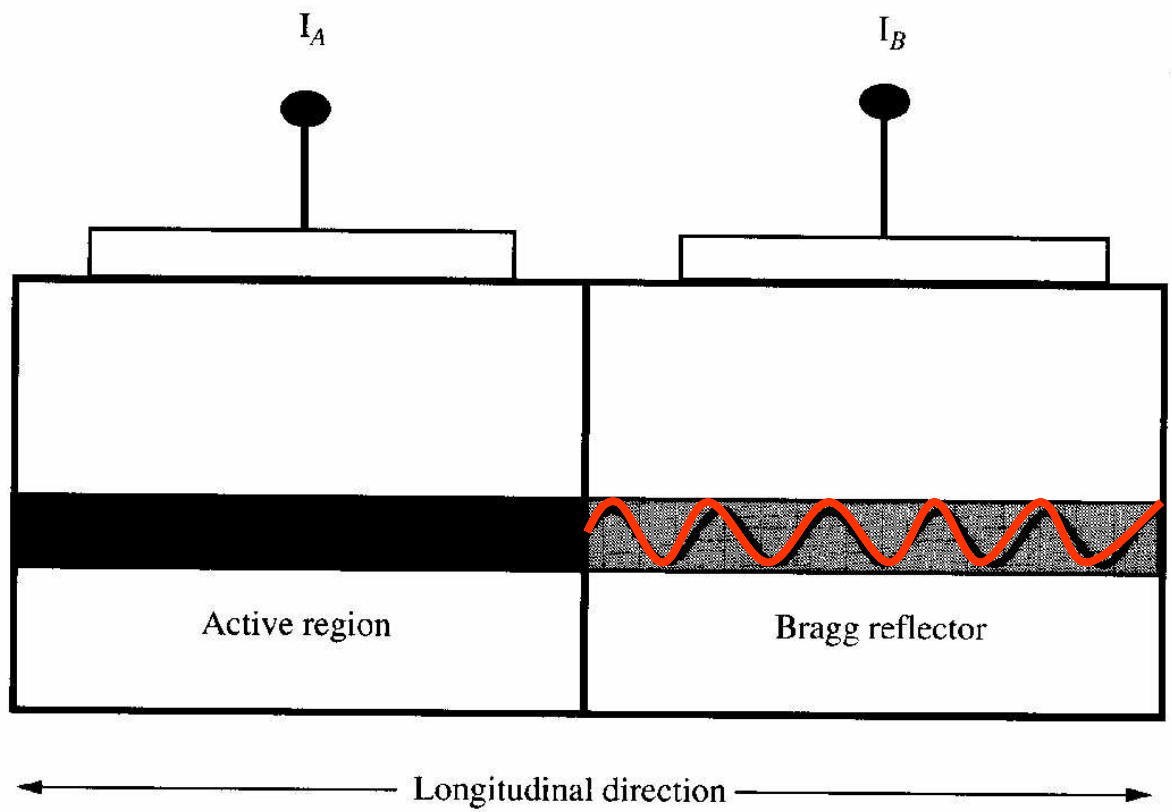


Figure 3.20 Illustration of a DBR LD.

Cavity Coupled Lasers

- The **coupled-cavity** laser has two FP resonant cavities, which can both be active (called **cleaved-coupled-cavity** or C^3 lasers) or one active and one passive.
- These lasers are illustrated in figure 3.21
- In either case, the basic principle to generate only a single longitudinal mode is illustrated in figure 3.22
- The wavelength of the longitudinal mode that can pass through both cavities should satisfy the constructive interference condition

Cavity Coupled Lasers

- Thus: $$\lambda = \frac{2L_1 n}{m_1} = \frac{2L_2 n}{m_2} \qquad \text{.......3.17}$$
- Where m_1 and m_2 are two integers. The modal separation is:

$$\Delta\lambda_{long} = M_1 \frac{\lambda^2}{2L_1 n} = M_2 \frac{\lambda^2}{2L_2 n} \qquad \text{........3.18}$$

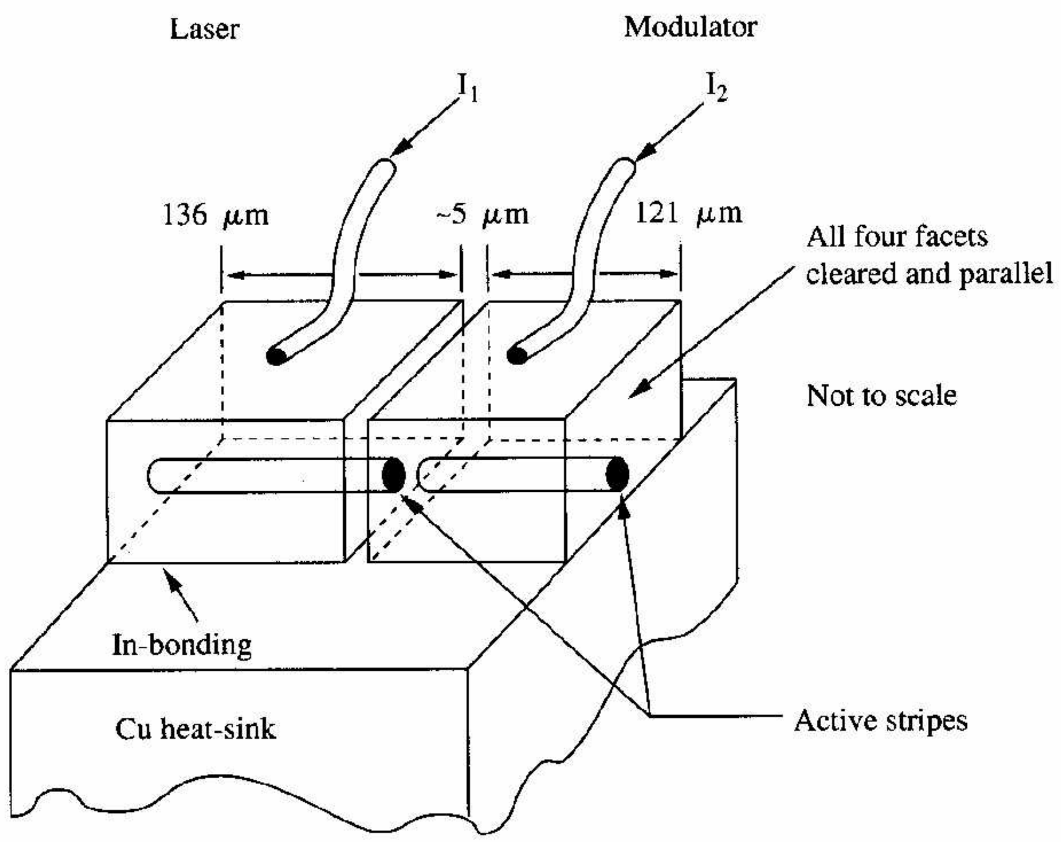
Where M_1 and M_2 are two mutually prime integers such that

$$\frac{L_1}{M_1} = \frac{L_2}{M_2} \stackrel{\text{def}}{=} L_0 \qquad \text{...............3.19}$$

From the above condition,

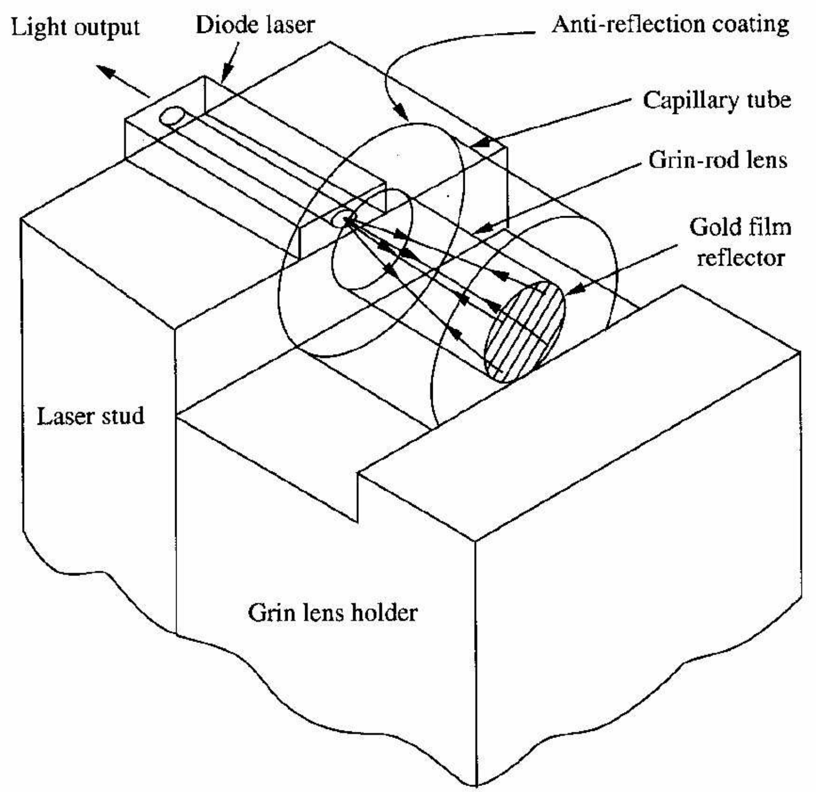
$$\Delta\lambda_{long} = \frac{\lambda^2}{2nL_0} \qquad \text{............3.20}$$

Cavity Coupled Lasers



(a) Active-active

Cavity Coupled Lasers



(b)

Figure 3.21 Illustration of coupled-cavity LDs: (*a*) active-active, and (*b*) active-passive.

Cavity Coupled Lasers

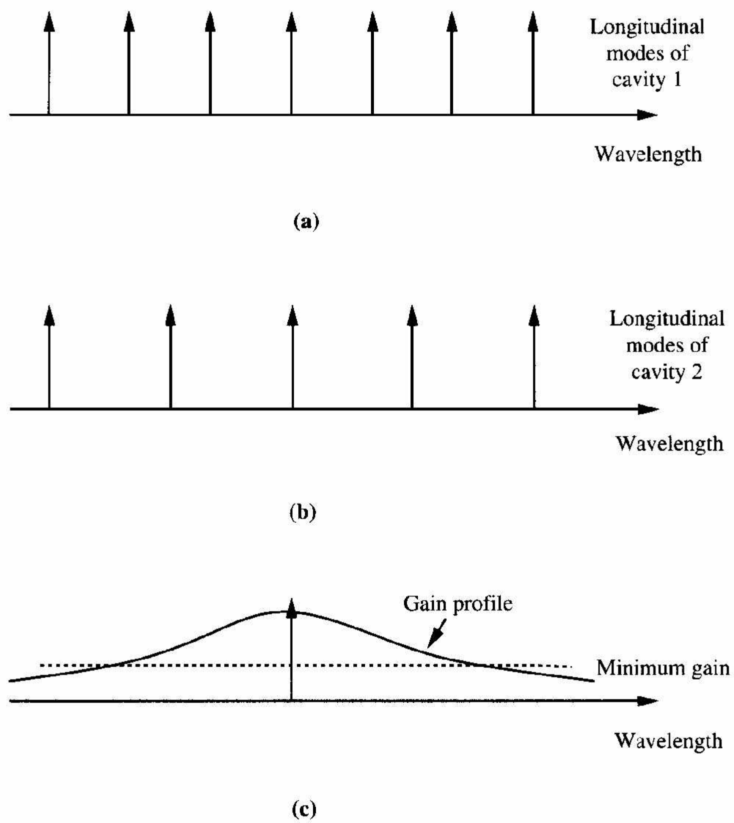


Figure 3.22 Principle of coupled-cavity laser diodes: (*a*) longitudinal modes of cavity 1, (*b*) longitudinal modes of cavity 2, and (*c*) only one common mode whose gain is greater than the loss in the gain profile.

Cavity Coupled Lasers

- When the modal separation is large enough, there is only one possible mode that has enough gain in the profile to lase
- For C^3 lasers, one of the current signals can be used for modulation and the other can be used to control the output light wavelength
- This is illustrated in figure 3.23. When the current increases, the refractive index of the cavity decreases; hence the output light wavelength decreases. From equation 3.17, the output light wavelength decreases.

$$\lambda = \frac{2L_1 n}{m_1} = \frac{2L_2 n}{m_2}$$

Cavity Coupled Lasers

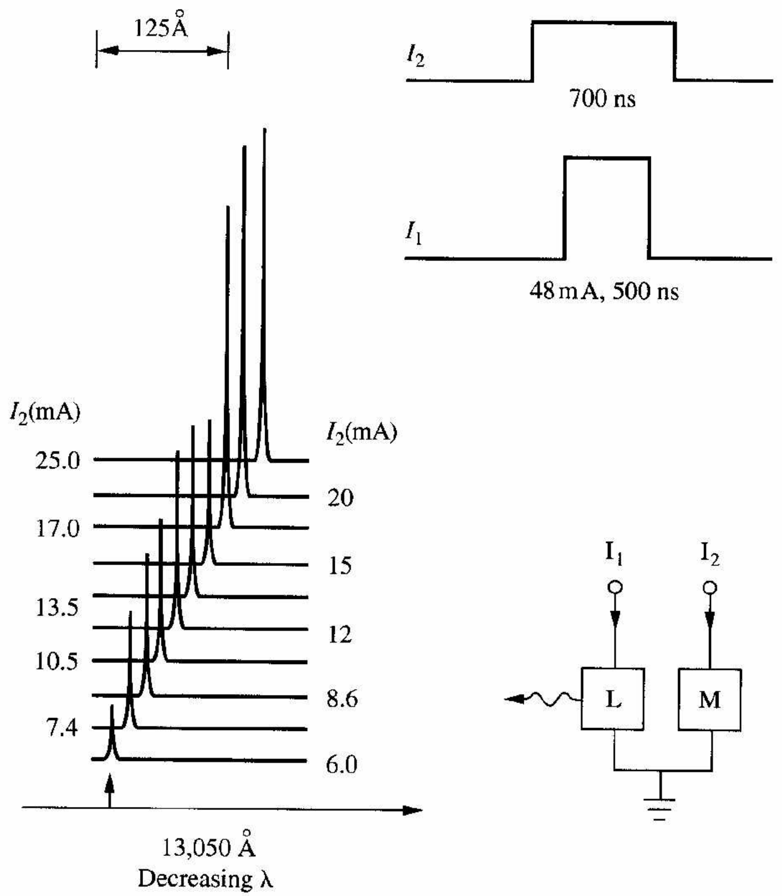


Figure 3.23 Frequency modulation of the C^3 Laser.

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Tuneable Lasers

- Three basic types of tuneable laser diodes based on DBR structures are shown in figure 3.28
- They have an active region denoted by A and a Bragg reflection region denoted by B
- For better tuning, some DBR's also include a phase control region, denoted by P
- In general, the output wavelength can be electrically tuned by adjusting the bias current of either B (Bragg reflection), P (phase) or both

Tuneable Lasers

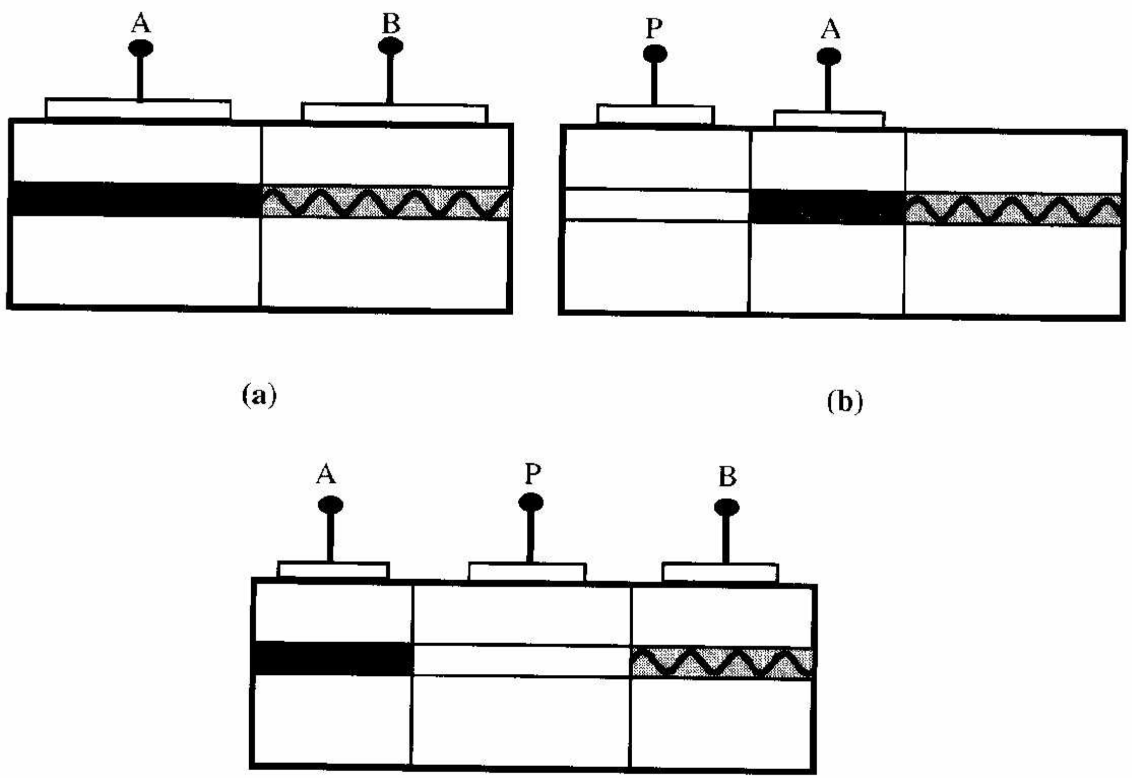

Figure 3.28 Tunable DBR lasers: (*a*) Bragg reflector tuning, (*b*) phase-section tuning, and (*c*) both Bragg and phase tuning.

Tuneability of DBR lasers

- The combination of active and phase regions can be considered as a special kind of FP laser, with one facet of zero reflection, and the Bragg reflection region can be considered as an optical filter
- Because of the narrow spectrum width of the Bragg filter, only one longitudinal mode can pass through the filter and other modes are suppressed
- When the bias current of the Bragg reflector is changed, the Bragg wavelength decreases as the current increases, equation 3.16.
- This means that the central wavelength of the bandpass Bragg filter shifts to a lower wavelength as the bias current increases

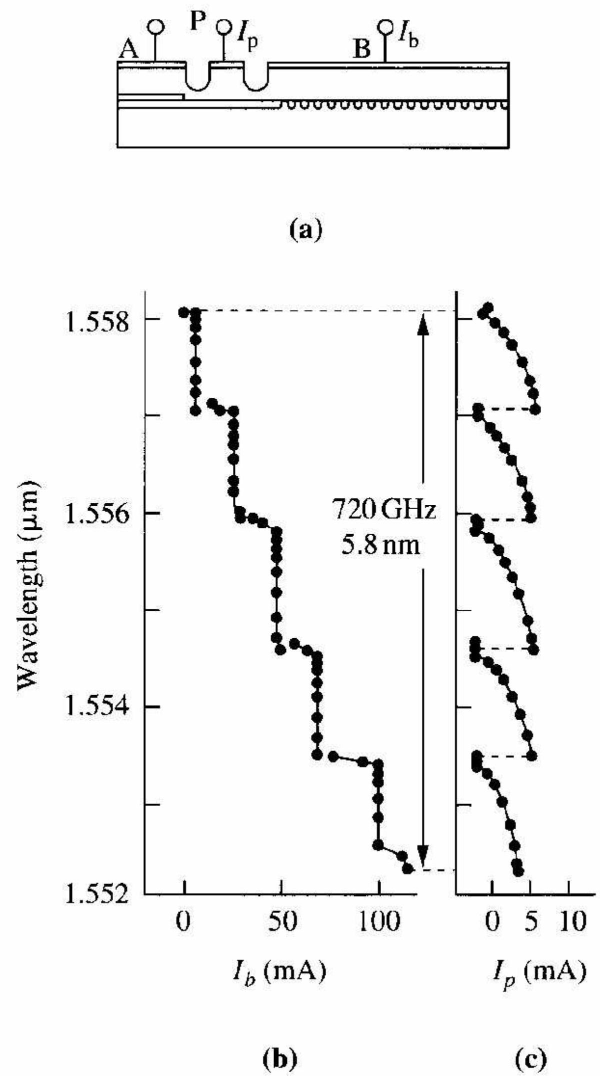

Figure 3.29 DBR-tuning frequency response: (*a*) Configuration (b) Bragg tuning only and (*c*) phase tuning only.

Tuneability of DBR lasers

- When the bias current of the phase section changes, its refractive index decreases
- The decrease in refractive index results in a decrease of wavelengths of all longitudinal modes. Figure 3.29c
- When the Bragg and phase controls are properly controlled at the same time, figure 3.30, a continuous wavelength tuning over 3.1 nm is achieved. At λ = 1.55μm, this is equivalent to 380 GHz tuneable frequency range.

Tuneability of DBR lasers

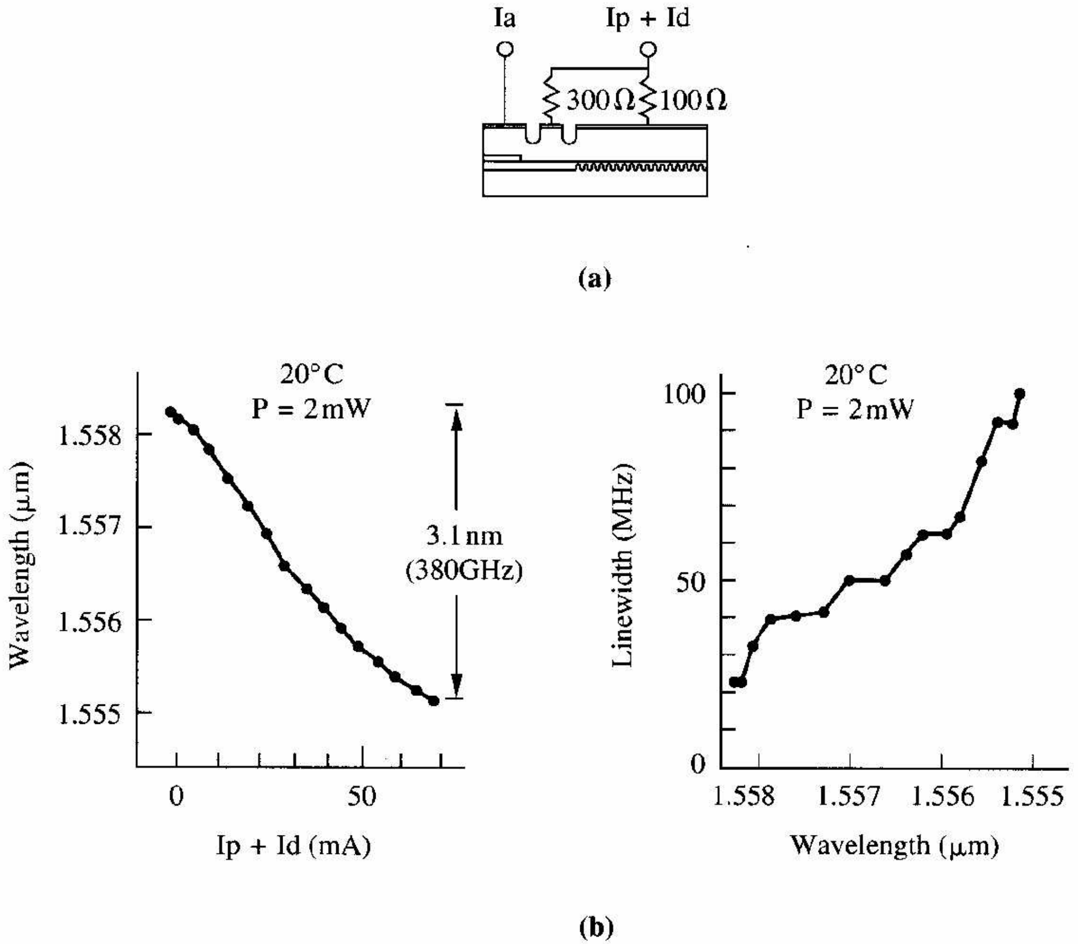

Figure 3.30 Both Bragg and phase-tuning frequency response of DBR lasers: *(a)* bias circuit and *(b)* frequency response.

Tuneability of DFB lasers

- Figure 3.31 illustrates two kinds of tuneable lasers based on DFB
- The first kind has a second phase control section and the second kind has two active control sections
- Because the Bragg reflection is inside the DFB laser section, tuning the active region changes the wavelengths of the longitudinal modes and the central wavelength of the Bragg filter at the same time.
- Therefore it is much more difficult to tune a DFB laser

Tuneable DFB lasers

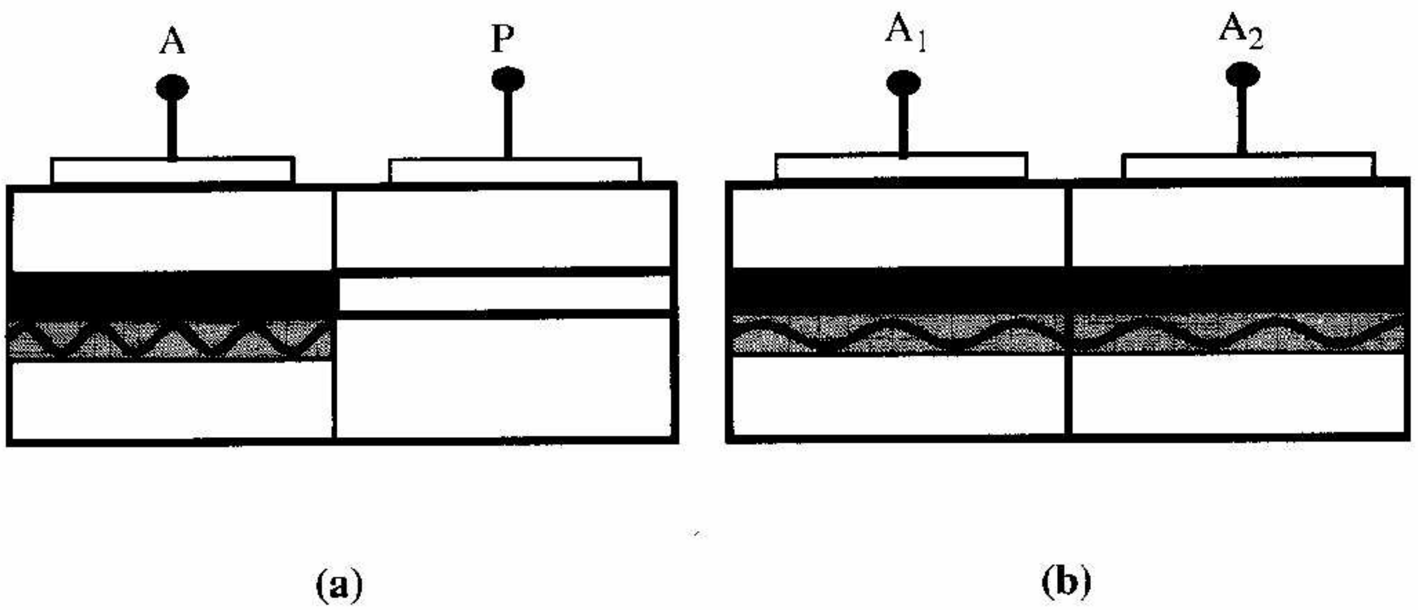

Figure 3.31 Tunable DFB lasers: (a) phase-section tuning and (b) two-active-section tuning.

The End